LEARNING STOICHIOMETRY:
A COMPARISON OF TEXT AND MULTIMEDIA INSTRUCTIONAL FORMATS

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ABSTRACT

Learning Stoichiometry: A Comparison of Text and Multimedia Instructional Formats

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Background: The current mode of stoichiometry instruction employs a passive pedagogy that consists of students reading, listening, watching, and memorizing disembodied facts, procedures, and principles in preparation for future application. But chemistry students are often subsequently unable to apply this stoichiometry knowledge in equilibrium and acid-base chemistry problem solving. Cognitive research findings suggest that for learning to be meaningful, learners need to actively construct their own knowledge by integrating new information into, and reorganizing, their prior understandings. Scaffolded inquiry in which facts, procedures, and principles are introduced as needed within the context of authentic problem solving may provide the practice and encoding opportunities necessary for construction of a memorable and usable knowledge base. The dynamic and interactive capabilities of online technology may facilitate stoichiometry instruction that promotes this meaningful learning.

Purpose: To compare students' performance after studying one of two cognitively informed sets of stoichiometry instructional materials in order to determine if the dynamic and interactive capabilities of online technology promote greater learning outcomes than studying from text-based materials alone.

Setting: Requests for volunteers, collection of background data, treatment assignment, and a post-treatment assessment were all delivered online. A second parallel assessment one-week post-treatment was administered in a proctored classroom on the Carnegie Mellon University (CMU) campus.

Participants: Volunteers of at least 18 years of age were solicited from incoming CMU freshman affiliated with either the Mellon College of Science (MCS) or the Carnegie Institute of Technology (CIT). Forty-five (out of 426 solicited) participants completed one of two sets of stoichiometry instructional materials within a six-week period in July and August, 2005.

Intervention: Volunteers were randomly assigned to one of two treatments--a text-only or technology-rich, dynamic and interactive stoichiometry review course.

Research Design: Randomized posttest-only controlled trial.

Data Collection and Analysis: Background data included participants' SAT scores, number of chemistry courses taken, and gender. Parallel posttests of stoichiometry concepts and procedures were administered two times post-treatment--upon completion of study materials and one week later. Participants' interactions with the technology-rich treatment were recorded in log files. Exploratory data analysis was performed to look for patterns in the data. Modeling of the data was executed by single regressions of posttest scores on treatment, background characteristics, and log files to determine the contribution of each variable to learning. A multiple regression of posttest scores on the variables significantly correlated with them revealed what proportion of the variability in posttest scores could be attributed to specific variables or interactions among them.

Findings: SAT scores and gender were stronger predictors of posttest performance than either treatment. Examination of the statistically significant correlation between SAT score and gender revealed a differential in the SAT scores of females and males admitted to MCS and CIT with males having higher scores overall. The mean SAT score for female volunteers was significantly lower than that for the female population. There was no such discrepancy between male volunteers and the male population. Within the technology-rich treatment group, participant interaction with the Virtual Lab simulation, but not SAT scores, is related to posttest performance. Whether this interactivity can offset possible gender effects is uncertain because of the small number of females in the technology-rich treatment group.

Conclusions: Future users of the online course should be encouraged to engage with the problem-solving opportunities provided by the Virtual Lab simulation through either explicit instruction and/or implementation of some level of program control within the course's navigational features. The variability of students' prior knowledge levels in quantitative areas points to a need for rigorous support systems during first-year courses in order to curtail poor performance that could result in increased attrition rates. One type of support system could be supplemental instruction grounded in findings from the learning sciences and facilitated by the dynamic and interactive features of online technology.

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PREFACE

Without John's ongoing love, encouragement, and understanding, this work would never have been realized. He has been my best friend for nearly 40 years. Marrying him was the smartest thing I have ever done and will ever do. This dissertation is dedicated to him.

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1.0 INTRODUCTION

Chemistry traditionally has been defined as the systematic study of matter and the changes it undergoes. This definition may have been adequate until the mid-part of the 20th century when natural science seemed to be clearly divisible between the physical (e.g., chemistry, physics, geology, astronomy) and biological (e.g., botany, zoology) sciences. Now, however, chemistry's "methods, concepts, and practices [have penetrated] virtually every nook and cranny of science and technology" (Amato, 1991, p. 1212). Modern day chemists' fields of study are often of a hyphenated nature (astro-chemistry, bio-chemistry, geo-chemistry) that reflects the emergence of new investigative arenas and the blurring of the lines of demarcation among the domains. Many of today's professions, such as medicine, engineering, dietetics, and pharmacy, rely on chemical principles and procedures. Even endeavors such as art restoration, patent law, culinary arts, and oenology are enhanced by chemical literacy. A 21st-century definition of modern chemistry is nearly impossible to derive; but an operational characterization of what chemists do may help to inform instruction for meaningful learning in this complex network of domains.

The practice of chemistry can be described by the valued work in which its practitioners engage. An analysis of the past 50 years' Nobel Prize citations, the ultimate recognition for work in chemistry, reveals that chemists explain phenomena, analyze substances, and synthesize new materials. News reports of chemical research support the prevalence of these three major endeavors (Evans, Leinhardt, Karabinos, & Yaron, 2006). In order to undertake their work, chemists employ a *toolbox* of qualitative and quantitative models and representations. However, an analysis of popular chemistry textbooks (the dominant vehicles for formal education in chemistry) reveals that nearly half the objectives address the contents of the toolbox. Although the remaining objectives can be categorized as explaining phenomena, nearly all involve the discussion of theories presented as established facts rather than as testable hypotheses, a problem that Schwab (1962) described as a *rhetoric of conclusions*. By not revealing the domain's exciting experimental work at the frontier of new knowledge development, these textbooks fail to reflect the authentic practice of chemistry (Evans et al., 2006). Clearly there is a disconnect between what is taught about chemistry in the classroom and how its practitioners work in the field. This disconnect may be responsible in part for the dearth of students that undertake its formal study after high school (Breslow, 2001) even though chemistry knowledge supports multiple 21st century career opportunities. Chemistry is often the gatekeeper course that filters out all but the brightest (and most tenacious) students. Chemistry content that more accurately represents the excitement of the valued activities of the domain, especially in introductory courses, may serve to encourage its pursuit as well as the development of a generative knowledge base.

1.1 STOICHIOMETRY

As one of the major tools in the chemistry toolbox, stoichiometry is a major focus of high school chemistry. Stoichiometry represents what is hard about learning chemistry. It is the chemical algebra that connects the *macroscopic* features with the *submicroscopic* interactions of the domain by using a set of abstract symbols and relying on the formal reasoning of proportional analysis. Stoichiometry usually is taught as a collection of procedural competencies disconnected from their applications and as preparation for use in other content areas, such as equilibrium and acid-base chemistry, that may or may not be addressed in the high school course. It is no wonder that stoichiometry is one of the least attractive and more difficult areas in high school chemistry.

Stoichiometry content commonly is reviewed early in the first semester of an introductory college chemistry two-course sequence. Although some professors provide direct instruction in stoichiometry, others require that students self-review. The need for a flexible and fluid use of stoichiometric concepts and procedures does not end with introductory college chemistry. Problem solving in the advanced coursework of physical chemistry and biochemistry also requires the application of this major tool of the chemistry toolbox. As such, stoichiometry can serve as a location for initiating pedagogical reform that links chemistry's disciplinary practice with the instruction and learning of one of its major tools.

1.2 INFORMING INSTRUCTIONAL DESIGN

Stoichiometry is taught during the high school years and reviewed early during the first college chemistry course as a collection of procedures, but it requires both procedural and conceptual applications in subsequent studies of equilibrium and acid-base chemistry problem solving. In order for a learner to develop the highly interconnected knowledge framework necessary for this complex chemistry problem solving, the topic of stoichiometry must move from being simply a collection of tools to being those tools in use (Evans et al., 2006). Much of the understanding of how new information is processed into such a framework comes from research into the learning of physics, algebra, and computer programming--areas whose natures are similar to stoichiometry in that they are rich in formal mathematical procedures undergirded by an abstract conceptual base.

Three findings from this research on learning are particularly appropriate to consider when designing instruction to promote fluid and flexible use of stoichiometric concepts and procedures. First, students construct their own understanding by actively processing incoming information in the service of reorganizing their prior knowledge. Second, this active processing is limited by a cognitive structure with a finite capacity for processing but essentially an infinite capacity for storage. As a result of this active processing, new information is encoded into long-term memory. Third, the context in which the new information is encoded and rehearsed influences its future retrieval and application. This chapter briefly examines the evidence for considering construction, cognitive capacity, and context when designing instruction. Chapter 2 reviews how this evidence has informed specific instructional practices in other areas of science instruction, practices that may be adapted for stoichiometry instruction.

1.2.1 Construction

The theory that knowledge is not passively received but actively constructed by learners from their experiences was first formalized by Piaget (1954). Piaget's ideas have been expanded and tested so that our current understanding is the following: During the process of learning the learners' prior knowledge both filters what is seen or heard and serves a framework for restructuring what is already known. The value of constructivist instruction lies in what it causes the student to do (Simon, 2000; Wheatley, 1991). Studies of students' alternative conceptions and expert-novice performance point to a constructivist theory of knowledge acquisition. The tenacity of students' alternative conceptions supports the claim that learning involves the unpacking of what is taught and a repacking with regard to the learner's prior knowledge, rather than simply the transmission of knowledge in final form from the mind of the teacher to the mind of the student (Ausubel, Novak, & Hanesian, 1978). For example, after completing a calculus-based physics course, nearly 66% of the students were unable to apply the concept of acceleration to a real-world situation (Trowbridge & McDermott, 1981). Without active integration into their own cognitive structures students seemed to maintain two parallel conceptual frameworks---one for solving exercises in physics class and one for explaining real-world phenomena. Similarly, Clement (1983) documented how students used *F=ma* in the classroom simultaneously with the idea that *motion implies force* in describing their real world experiences.

Evidence from expert-novice studies also supports a constructivist theory of knowledge acquisition. Experts in a number of fields, such as chess (De Groot, 1965), physics (Chi, Feltovich, & Glaser, 1981), and computer programming (Ehrlich & Soloway, 1984), work with new information in their respective domains differently than do novices. This differential information use is a function of both the amount and organization of domain-specific knowledge that an individual brings to a given situation. Experts have developed conceptual frameworks or schemas that organize information into meaningful patterns. (Rumelhart & Norman, 1981). These schemas, or conceptual frameworks, facilitate both recall and the interpretation of environmental events including problem solving (Chase & Simon, 1973; Glaser & Chi, 1988; Simon & Chase, 1973). When these schemas are well rehearsed as the result of thousands of hours of deliberate practice, they can be processed automatically without conscious effort, thereby freeing up cognitive resources for processing further information yet to be learned (Ericsson, Krampe, & Tesch-Romer, 1993).

Students have experienced the effects of stoichiometry in their everyday lives--from adjusting a motorcycle’s carburetor to produce the optimal mix of air and fuel for peak performance to modifying the ingredients in a cookie recipe to yield chewier or crunchier morsels. What makes stoichiometry so difficult to learn and to understand is that these macroscopic features (peak performance, texture) are emergent properties resulting from actions at the atomic or molecular level (Chi, 2005; Chi & Roscoe, 2002; Penner, 2000). These submicroscopic actions operate at a non-human scale and are unable to be directly manipulated or experienced. Therefore, developing an intuition for connecting these macroscopic features with submicroscopic interactions is difficult (Yaron, Leinhardt, & Karabinos, 2004). Still another learning challenge is the mastery of the representational system of symbols, formulas, equations, and mathematical manipulations used to describe and explain these unseen submicroscopic interactions that give rise to the macroscopic features. Expert chemists move freely among these three levels as they pursue their work, including that of instruction (Johnstone, 2000). Yet students, whose knowledge framework is rudimentary at best, have great difficulty understanding their teachers when explanations move away from the macroscopic level with which they have everyday experience. When stoichiometry instruction occurs only at the abstract representational level with no opportunity for learners to build connections to concrete experiences, learning is memorable only for the frustration caused. Effective stoichiometric instruction would promote student exploration and development of cognitive connections among the macroscopic, submicroscopic, and representational aspects of stoichiometric tools. Multimedia simulation is an instructional method that may successfully support such cognitive exploration and development.

1.2.2 Cognitive structure

Although learning requires the active processing of information, the amount of information that can be consciously processed at any given time is limited to about five to seven elements or chunks (Miller, 1956; Simon, 1974). What constitutes an element or chunk of information is affected by the organization of the prior knowledge (i.e., schemas) of the processing individual. The learner's cognitive load is limited to the total number of chunks that can be consciously processed at any given time. On the other hand, the capacity to store automated schemas is practically unlimited. Therefore, development and storage of schemas is a major goal of learning for problem solving, since schemas can increase the amount of information that can be actively processed simultaneously by effectively coalescing multiple elements into a single chunk. Well-developed schemas can be processed automatically without conscious effort and thereby can free processing space for other activities. Limited processing capacity and schema development can explain the expert-novice differential in memory and problem-solving performance. In physics problem solving, experts' schemas permit classification of problems into categories based upon a solution process. Novices' lack of functional schemas results in the learners' attending to surface descriptive features of a problem, which does little to ameliorate the cognitive load of means-end analysis during the solution process (Chi, Glaser, & Rees, 1982).

Although the amount of information that can be processed at a given time is limited, independent auditory and visual channels can simultaneously process two modes of input (Baddeley, 1986) and build referential connections between them. Tasker and Dalton's (2006) audiovisual information-processing model is a blend of Johnstone's (1997) information-processing model of chemistry learning and Mayer's (1997) multimedia model of instructional explanations in science. According to this composite model, verbal and visual stimuli are perceived in separate parts of sensory memory; selected, integrated, and processed within a limited working space; and encoded into long-term memory for efficient retrieval and transfer to new situations. Research on the implications for presentation of audiovisual information has provided evidence that working memory capacity can be expanded slightly by mixing the senses during instruction (Moreno & Mayer, 2000; Sweller, 1994). Specifically, learners may be able to process information more easily when part is presented visually and part is presented acoustically rather than all being conveyed through a single sense. This structure of the active-processing component of memory (working memory) suggests that a multimedia design for stoichiometry instruction may be especially useful.

1.2.3 Context

Active processing results in the encoding of new information that stimulates the restructuring of the learner's conceptual framework. Well-designed practice events provide encoding opportunities. Because each encoding opportunity can result in more (stronger) connections within existing knowledge in long-term memory, practice and long-term retention are interconnected. Development of expertise is strongly related to the amount of deliberate practice during which a continuous monitoring of performance occurs (Ericsson & Charness, 1994; Ericsson, Krampe, & Tesch-Rome, 1993). For encoded knowledge to be used, however, it must be retrieved and transferred back to active processing as needed. This transfer is maximized when the context of retrieval and encoding match (Tulving & Thomson, 1973). The traditional introduction of a principle or theory before its application does not appear to promote encoding since the abstract ideas are disconnected from use. Likewise, rote or memorization practice does not stimulate encoding of new information within the learner's prior knowledge base. The absence of retrieval cues can result in *inert knowledge* (Whitehead, 1929) that is easily forgotten and is unavailable for future application. Furthermore, the use of knowledge across contexts is difficult when information is processed in only a single context (Bjork & Richardson-Klavhen, 1989). In order for knowledge to be flexible and to be applicable in multiple situations, there is a need for the kind of practice that incorporates opportunities for encoding of concepts and procedures in a variety of contexts that will promote more highly integrated connections within the learner's knowledge base (Gick & Holyoak, 1983). When abstract stoichiometry procedures are taught divorced from their use in real-world chemical contexts such as equilibrium or acid-base problem solving, minimal opportunity for encoding (to promote subsequent recall or application) is provided for the learner. In a similar fashion, the rote practice of these stoichiometric procedures in order to pass a mastery test may do little to promote the retention and retrieval of this knowledge for use in future instantiations of chemistry problem solving.

To develop a memorable and usable knowledge base, instruction should employ an approach in which stoichiometry concepts and procedures are introduced as needed within the context of solving an authentic real-world problem. This type of approach would connect the learning of stoichiometric tools to their intellectual and practical use, thereby providing the student with multiple opportunities for encoding and practice. But such authentic inquiry is complex and time consuming. Novices rarely, if ever, can undertake this process alone but rather need to work as apprentices supported by more knowledgeable members of a particular community. A simulated reality of an authentic problem-solving situation that allows learner-imposed sequencing of actions that are scaffolded with feedback, including generalized hints and goal reminders, can provide both the interaction and engagement necessary for successful learning in a manner approaching that of one-on-one tutoring (Bloom, 1984).

1.3 USING TECHNOLOGY TO FACILITATE INSTRUCTION

The findings from research on cognition can inform instructional design to make stoichiometry easier and more interesting to learn. Any well-designed instruction's delivery must also promote the active construction of knowledge, be mindful of the processing capacity of the learner, and provide multiple opportunities for encoding. The traditional *explain-apply* pedagogy, by which stoichiometry is presented as a collection of procedures to be memorized and held in abeyance for future use, is not working. Even after participating in multiple learning opportunities (high school courses, review for college mastery tests), college chemistry students do not exhibit fluid and flexible use of stoichiometric competencies in equilibrium and acid-base problem solving. Although instructional technology (i.e., the tools and methods of instruction) has been used to deliver instruction for some time, it is not the technology that is most important but rather the activity it enables (Oblinger, 2005). The optimum use of technology can facilitate learning but under certain conditions technology may be superfluous and even impede learning.

1.3.1 Technology: Facilitating or superfluous?

Scientific discovery is in essence original learning. The relationship between technology and scientific discovery is vividly portrayed by the work of Robert Boyle, a 17th-century natural philosopher. Often considered as one of the fathers of modern chemistry, he was the first prominent scientist to perform controlled experiments and publish his work complete with detailed methods, materials, and quantitative data. Boyle's empirical study of the physical properties of gases would not have been possible without the technological developments of specially blown glass vessels that could withstand high pressures as well as a vacuum pump of his own design (Hall, 1967). His discovery of the inverse relationship between gas pressure and volume (k=PV) is familiar to every chemistry student as Boyle's Law. It was not the special glassware or vacuum pump that led to discovery of this law but rather how these tools facilitated an activity (measurement) that revealed a relationship between the pressure and volume of a gas.

A cursory inventory of school lab equipment may include pan balances with sets of brass weights, pH paper, test tubes, and thermometers. Due to cost constraints, this level of instrumentation in classroom labs hardly matches that found in modern chemistry laboratories but is rather characteristic of a 1950's venue. When instruction uses the traditional explain-apply pedagogy in which students read, listen, and/or watch before memorizing sets of procedures and principles, such technology may be sufficient to supplement, by confirmatory activities, what has already been explained. Even if cost were not a factor and school chemistry labs were equipped in a manner comparable to those at leading research facilities, the complexity of the domain's structure along with the need for practiced kinesthetic skills to extract quality data preclude the ability of novice students to infer the logical framework of 21^{st}-century chemistry.

The acquisition of new chemical knowledge has advanced rapidly since the time of Boyle due to the development of tools such as nuclear magnetic resonance spectrophotometers and methodologies such as DNA profiling. There is no doubt that the pace of this research has increased by orders of magnitude in recent decades due to the development and implementation of digital and electronic technology. Boyle's glass bottles and vacuum pump aided in the legitimizing of chemistry as an empirical science (as opposed to the mysticism of alchemy) in the 17^{th} century. In an analogous fashion, learning research has provided evidence for developing instructional pedagogy that cognitively activates the learner through methods such as authentic inquiry. Just as digital and electronic equipment have facilitated the ways in which 21^{st}-century chemists can acquire knowledge about their domain, so too may the affordances of online technology be able to support the way in which 21^{st}-century students learn about the domain.

1.3.2 Technology to support the learning of stoichiometry

An extensive array of technological tools has evolved over the last two decades to support instruction in math and science. Programmable electronic calculators have done much to enhance problem solving in mathematics and other quantitative domains such as chemistry by supporting the user in complex data analysis. The communications technology of the World Wide Web supports classroom instruction with programs such as *WebAssign* (North Carolina State University) that deliver homework problems to students, grade their responses, provide them with immediate feedback, and maintain a grade book for the instructor. *Just-in-Time Teaching* (Novak, Patterson, Gavrin, & Christian, 1999) uses web-based preparatory assignments to engage students actively in learning before coming to lecture as well as to inform the instructor of their state of prior knowledge so that lectures can be adapted appropriately. By reading student submissions prior to the start of classes, faculty can adjust classroom lessons just in time to suit the students' needs.

Modern computer hardware and software along with the World Wide Web are capable of providing an environment for the generation of meaningful inquiry, the collection of data and its analysis, as well as timely and appropriate support and feedback. A multimedia delivery system (i.e., text, sound, images, movies, simulations, etc.) allows presentation of concepts that are difficult to explain in a static text-only format whether on the chalkboard or in textbook. Links in hypertext and images encourage branched (non-linear) instruction to support individual learners' needs as opposed to the one-size-fits-all mode of traditional content delivery. Other opportunities for interaction include immediate and explicit feedback to student responses in problem solving as well as implicit feedback from their manipulations of dynamic learning objects. Furthermore, technology does not limit learning to a specific time or place but allows it to occur at any time or in any place. Development of communities of learners may be facilitated through email or message boards via synchronous or asynchronous (threaded discussion) communications. With these various capabilities, modern electronic technology via the World Wide Web or CD-ROMs may offer students an educational venue capable of facilitating the goal of meaningful learning (Ausubel et al., 1978) without regard to inequalities in local social, financial, structural, or intellectual resources.

In a rapidly changing, knowledge-based society it is easy to be lured into believing that the bells and whistles of modern digital electronic technology along with access to the World Wide Web will produce the type of learning needed for intuiting stoichiometry's use in complex problem-solving situations. It is true that technology provides the tools to create interactions (e.g., simulations, feedback, tutorials, etc.) that may facilitate a learner's construction of a fluid and flexible knowledge framework. It is also true that the World Wide Web provides quick access to a vast repository of information (content)--a virtual library. But to exploit the unique capabilities of these media fully, they must be manipulated by instructional designers in ways that effectively promote learning. It is the methods developed from the findings of learning research, not the media through which they are delivered, that are the keys to effective instruction (Clark & Mayer, 2003).

1.4 SUMMARY

As a central science, chemistry may be a good location from which to design instruction that promotes meaningful learning. Chemistry is challenging to learn since its explanatory power lies with entities and processes occurring at a scale below that of human perception (submicroscopic). Observations, including measurements, however, occur at a macroscopic level. The ability to make a connection between these two levels is further complicated by the mathematical modeling and descriptive representations of the domain (Johnstone, 2000; Yaron et al., 2004). Traditional chemistry instruction employs an explain-apply pedagogy consisting of students reading, listening, watching, and then memorizing disembodied facts, procedures, and principles in preparation for future study and participation in the domain. On the other hand, practitioners of chemistry work at analyzing substances, synthesizing new materials, and explaining phenomena. During these activities they implement a collection of mathematical tools and symbols as needed. This disconnect between the practice of the classroom and in the field does little to guarantee memorable learning (Evans et al., 2006). The difficulty that most students have in developing stoichiometric competencies that can be intuited for use in the study of subsequent chemistry topics such as equilibrium and acid-base chemistry epitomizes the problem with the current mode of instruction.

The development of digital electronic technology and the vast information accessibility of the World Wide Web hold the promise of a medium that can provide tools to facilitate the development of interactive learning environments in the service of promoting the type of learning needed for fluid and flexible use of the chemistry toolbox. Yet more than 50 years of content-delivery-technology research has shown that it is not the medium but rather the methods of instruction that affect learning. To exploit the unique capabilities of a “technology-rich learning environment" (Lajoie & Azevedo, 2006), a consideration of the findings from behavioral, information-processing, and sociocultural aspects of learning research may support the most effective instruction. Designers should consider that learners actively construct meaning through integration of new information and subsequent reorganization of prior knowledge, that human cognitive architecture controls what and how much information can be processed, and that attention to the context of instruction presents opportunities for developing the flexible knowledge base needed for effective problem solving.

1.5 PURPOSE OF THE STUDY

The purpose of this study is to compare student performance on a test of stoichiometry topics after studying one of two cognitively informed sets of instructional materials in order to determine if dynamic expositions, immediate supportive feedback, and an overarching cover story facilitated through online technologies promote greater learning outcomes than does studying text-based materials alone. The study focuses on students' development of the stoichiometry competencies needed for participation in equilibrium and acid-base chemistry problem solving. These topics are grounded in the flexible use of a set of stoichiometry tools taught during a high school course and reviewed in some manner during the first semester of an introductory college chemistry course. The study also seeks to determine if cognitively informed instruction enhanced by the affordances of multimedia technology can match or exceed the effect of students' prior knowledge of chemistry and/or mathematics as exhibited by performance on standardized examinations. Finally, the study seeks to determine if there are specific study practices facilitated by online technologies that are related to learning stoichiometry.

The candidate course for this study was designed and developed collaboratively by experts in chemistry content, educational psychology, instructional design, and multimedia technology in order to produce a product that optimally integrated chemistry knowledge with its methods and medium for instruction. The candidate course was compared to several other available online courses of similar content to ascertain the degree to which the instruction was cognitively guided. A set of text-based study materials used as an alternative treatment included the same content and instructional methods but not the delivery capabilities of a technology-rich online learning environment.

1.6 RESEARCH QUESTIONS

The study aimed to answer the following questions:

1. To what extent does receiving instruction in a technology-rich learning environment that incorporates a dynamic interface, timely and informative feedback, and an overarching storyline, influence the learning of stoichiometry?
2. How are background experiences and characteristics related to the learning of stoichiometry?
    a. How is the degree of prior knowledge of math and chemistry related to the learning of stoichiometry?
    b. How is the demographic of gender related to the learning of stoichiometry?

3. To what extent do a technology-rich environment and student background experiences and characteristics work together to influence the learning of stoichiometry?
4. How are learning practices that are facilitated by a technology-rich environment related to the learning of stoichiometry?

1.7 CONTRIBUTION TO THE FIELD

This study contributes to several fields of research and practice. In a very specific sense it advances chemistry education research at the interface between the high school and the university by developing and testing the effectiveness of a review course for stoichiometry, one of the most important yet difficult sets of tools needed for the study of topics such as equilibrium and acid-base chemistry during the freshman introductory chemistry course. The development of the instructional materials was informed by the acknowledged difficulties in the learning of chemistry due to the domain's tripartite logical structure (Johnstone, 2000; Yaron et al., 2004) as well as by the desire to situate instruction within an authentic activity of chemists (Evans et al., 2006). Another contribution of this work is to the research on teaching and learning in technology-rich environments (Lajoie & Azevedo, 2006). By using contrast groups to compare learning outcomes from cognitively informed instruction both within and in the absence of a dynamic and interactive environment, this research can lay the groundwork for further investigation into specifically which aspects of technology-rich environments optimize the learning process. Finally, the results from this research may serve to guide reform instruction in chemistry in the service of developing scientific literacy for all citizens. Instructional methods informed by the findings of learning research and delivered through technology-rich environments accessible through the Internet or CD-ROM may be the means by which access to high quality education is not limited by the lack of local financial, social, structural, or intellectual resources.

1.8 LIMITATIONS OF THIS STUDY

The study is limited by two factors related to the sample. First, the study was conducted with participants from a single upper-level university (Carnegie Mellon University) and results may differ with participants from other environments. Second, the sample turned out to be smaller than expected. The study was run during the summer with incoming university freshmen. Although equivalency of groups was generated through random assignment of solicited volunteers from a population of about 400 students, only 45 completed the study. Another limitation may be the nature of the posttest questions. These questions were developed from national standardized exams and consisted of both procedural and conceptual items that would be addressed by a traditional course. Authentic, ill-structured, real-world problems that require an intuitive approach were not tested even though it may be that type of problem solving that working with simulations and other affordances of a technology-rich environment supports.

2.0 REVIEW OF THE LITERATURE

This chapter reviews of the literature pertinent to the study. First, the research on the particular difficulties of learning chemistry with special emphasis on stoichiometry is summarized. Second, a review of tested and effective, research-informed science instruction is presented. Third, literature on the ways in which online technology may be able to deliver effective instruction is reviewed. Finally, a comparison of several online chemistry courses is reviewed to ascertain the degree to which (a) instruction was cognitively guided, and (b) features of online technology were implemented in the service of learning.

2.1 CHALLENGE OF LEARNING CHEMISTRY

Chemistry is difficult to learn because of the intrinsic load, or complexity, of its logical structure as well as the extraneous load imposed by the methods of its instruction (Sweller, Van Merrienboer, & Paas, 1998). Problem solving in chemistry requires a flexible manipulation and integration of the concrete and abstract levels of the domain’s structure. Instruction that fails to consider the psychological characteristics of the learner will not succeed in promoting the development of such a generative knowledge base.

2.1.1 Structural challenges to learning

To appreciate the complexity of learning chemistry, consider the following situation. The contents of two test tubes, each containing clear solutions, are mixed together in a third test tube. The contents of the third test tube appear as a clear solution with a bright yellow substance that precipitates (falls) to the bottom. The reaction is represented by the following equation:

$$Pb(NO_3)_2(\mathit{aq}) \quad + \quad 2\ KI(\mathit{aq}) \quad \rightarrow \quad PbI_2(\mathit{s}) \quad + \quad 2\ KNO_3(\mathit{aq})$$

This chemical equation is itself a dense expression to comprehend. Each single uppercase letter or uppercase letter followed immediately by a lowercase letter is an element's symbol. Groups of these symbols represent formulas of compounds. Lowercase letters enclosed in parentheses indicate the physical state of the substance immediately preceding it (e.g., *aq* indicates the compound is dissolved in water). The numerals have a dual function in this chemical equation. Subscripts represent the ratio of elements in specific compounds. The subscripts outside of parentheses are distributive in nature and apply to each element inside. Subscripts inside parentheses refer to the adjacent element only. Coefficients immediately preceding formulas represent the ratios of substances reacting and formed. For all of these functions, the numeral *1* is not represented but is *understood*. All chemical equations obey the Law of Conservation of Matter so that the same number of each element's atoms must appear on both sides of the yield sign (arrow). The learner must know the notational system and how ratios operate in order to interpret the chemical equation correctly.

The chemical equation written above does not represent a one-to-one-to-one correspondence of the three levels at which chemistry operates. Integrating this submicroscopic representation with the macroscopic observation in the third test tube is not straightforward. The amount of precipitate (PbI_2) produced is reported in macroscopic units--grams. But there is no simple connection between these units and the ratios of individual particles specified by the balanced chemical equation. Atoms and molecules react as individual entities; chemists measure them with mass units. To relate these two phenomena, a special amount of substance is needed. The mole is this amount of substance and it represents an extremely large number ($\approx 6.02 \times 10^{23}$, or 602 sextillion) of these submicroscopic entities, a quantity that can be measured in macroscopic units (e.g., grams). When working with chemical reactions students must move back and forth between the submicroscopic and macroscopic levels as well as work with representations of single entities that are measured by the masses of collections of them.

The balanced equation is a model of interaction at the submicroscopic level. This model does not account for unused materials. At the macroscopic level, however, the chemist rarely has masses of reactants whose molecular composition is exactly in the ratio specified by the chemical equation. Something is always *unreacted* and therefore *left over*. Students have difficulty relating this unreacted material at the macroscopic level to the abstract representations at the submicroscopic level. They may be able to determine mathematically which reactant limits how much product ultimately is produced, but often are unable to diagram the final composition of a reaction mixture (that includes unreacted material) at the submicroscopic level. They simply include this unreacted material on the product side of the chemical equation (Nurrenbern & Pickering, 1987; Sanger, 2005; Sawrey, 1990).

2.1.2 Instructional challenges to learning

The manner in which chemistry content, including that of stoichiometry, is explicated to students often presents another challenge to their learning. Divorced from its use in the field or from what is familiar to students, stoichiometry is taught as a collection of procedural competencies to be learned as preparation for use in future course content areas. Success in high school chemistry involves the ability to execute multistep abstract algebraic exercises rapidly and accurately. For more than 50 years chemical educators have been seeking explanations and solutions for the difficulty that many students exhibit with this aspect of chemistry instruction. Proficiency with these exercises appears to be related to proportional reasoning ability (Ward & Herron, 1980). Yet when proportional reasoning ability is assessed with instruments such as TOLT[1], only 50% of high school students are deemed to be capable of formal operations such as proportional reasoning.

In an effort to aid students in overcoming this *handicap*, chemistry instructors have developed a procedure known as dimensional analysis, or the factor-label method. Dimensional analysis supports proportional reasoning skills by showing how the units of measure are assigned and transformed during the arithmetic computation of ratios and proportions. However, this way of thinking through chemistry problems has itself become yet another routine to be memorized (Herron, 1975; Robinson, 2003; Wheeler & Kass, 1977). Such a mechanistic approach to stoichiometry problem solving results in knowledge that is fragmented or inert--able to be remembered in similar problem-solving situations (e.g., a unit test) but not available for use in new venues such as equilibrium applications (Brown, Collins, & Duguid, 1989; Whitehead, 1929). Mechanistic learning of this type also tends to block reflective competence on the part of the students, leaving them unable to learn from the problems they have done (Hiebert, 1992; Hiebert & Wearne, 1985). The stoichiometric problem-solving ability of students with high math anxiety (in addition to low proportional reasoning capabilities) does not improve with instruction of dimensional analysis techniques (Gabel & Sherwood, 1983). This finding is not surprising

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[1] Test of Logical Thinking

considering that social transmission through interactive, rather than passive, processes is necessary for the development of mental structures such as proportional reasoning ability (Piaget, 1964). Robinson and Niaz (1991) found that students in an interactive discussion (teacher-facilitated) treatment group performed significantly better on the class examination than did the control lecture group even though the treatment group had addressed fewer example problems. Actively involving students in the learning process whether in lecture or small group discussion improves performance (Gabel & Bunce, 1994). Furthermore, instruction that employs strategies such as diagrams and analogies as opposed to multiple examples using dimensional analysis is significantly more effective for students with high math anxiety probably because such an approach efficiently makes use of both the visual and verbal components of their memory structure (Gabel & Sherwood, 1983).

Instruction that leads to proficiency with solving algorithmic exercises does not translate to the learning of chemical concepts (Nakhleh, 1993; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering; Sawrey, 1990). Consistent with Ausubel's meaningful learning theory (Ausubel et al., 1978), conceptual knowledge is a significant predictor of problem-solving ability in chemistry (Ashmore, Frazer, & Cassey, 1979; Frazer, 1982). Although requisite concepts are necessary, they are not sufficient for successful problem solving in chemistry. An inability to recognize relationships among chemical concepts prevents students from applying their knowledge in new problem situations (Sumfleth, 1988).

Kempa & Nicholls (1983) found that the cognitive structures of good chemistry problem solvers were more highly networked than those of less successful problem solvers. Furthermore, with poor problem solvers the networking of abstract concepts was particularly lacking, a serious deficiency in that two of the three levels of chemistry knowledge (submicroscopic and symbolic) deal with abstractions. Gabel and Bunce (1994) suggest that it is this networking of concepts in long-term memory and the subsequent ease of transferability to working memory that determines success in chemistry problem solving. Integration of concepts is particularly difficult in chemistry because of the tripartite (macroscopic, submicroscopic, symbolic) nature of the domain that often requires movement among all three levels when solving a chemistry problem. Students must be explicitly taught, for instance, how to convert a symbol to the meaningful information that it represents (Johnstone, 1991). When achievement of students explicitly taught the conceptual underpinnings of stoichiometry is compared to that of students taught in the traditional algorithmic manner, the former significantly outperform the latter on a developer-based test (Dori & Hameiri, 2003). Unfortunately, teachers in introductory courses often only provide algorithmic formulas for solving these problems rather than requiring students to apply conceptual reasoning before executing a computation. When chemical knowledge is acquired in only one context (e.g., traditional textbook algorithmic exposition), the number of associations constructed may not be sufficient to provide the flexibility and accessibility for application of the knowledge in a different context.

Without the integration of the three levels of chemistry knowledge in long-term memory, working memory will be overloaded at the outset of the problem solving process (Reid & Yang, 2002). Simultaneous introduction of all three levels (what took over a hundred years in the chemistry community to develop) truly will overload processing capacity. Learners cope cognitively by constructing alternative frameworks (sometimes misconceptions) or by trying to store the information separately and unattached. Integration of the three levels of chemistry knowledge should be a gradual process that begins with a familiar context so that there are already anchors in long-term memory on which to attach new knowledge (Johnstone, 2000).

2.1.3 Summary

Chemistry, as exemplified by stoichiometry, is hard to learn. The difficulty with the content is in large part due to the conceptual movement among macroscopic, submicroscopic, and symbolic levels of knowing on one hand and the underlying mathematical requirements of proportional reasoning on the other. In an effort to simplify learning of the routine stoichiometry problems addressed in high school chemistry, instruction has focused on algorithmic execution of procedures with little or no emphasis on conceptual understanding or variable contexts. Students' success with these algorithmic procedures, however, does not promote their conceptual understanding. The inability to recognize relationships among concepts prevents them from intuiting stoichiometry's application to college chemistry topics such as equilibrium or authentic real-world problem solving. Engaging students in interactive problem solving as well as employing visual and verbal strategies to explicate example problems have been shown to be effective in promoting meaningful stoichiometry learning.

2.2 INFORMING STOICHIOMETRY INSTRUCTION

Chemistry is hard to learn because of the domain's structure and the use of instructional strategies that fail to consider the psychological nature of the learner. Research findings from the science of learning during the past half century have produced theories that help to explain the processes of human cognition. We have examined the evidence supporting the consideration of construction, cognitive capacity, and context when designing instruction. The creation and testing of instructional practices based on this evidence would be a systematic way of developing strategies for stoichiometry instruction. When principles of good instruction are based upon an integration and application of tested theories of learning from behavioral, information-processing, and sociocultural research, teaching itself becomes a scientific endeavor (Handelsman et al., 2004). This section discusses tested pedagogical methodologies that respond to the need for active engagement by the student in constructing knowledge, the need to manage a limited processing capacity, and the need for context to provide encoding opportunities.

2.2.1 Active engagement by the student

Chemistry classes traditionally have relied on transmission of content through lectures and confirmatory cookbook-style laboratory exercises, neither of which are effective in producing the fluid and flexible use of the domain's concepts and procedures. This view of chemistry, or any other science domain, as a static codified body of knowledge to be taught to students contrasts with the practicing chemists' goal of generating solutions to real-world problems through active construction of relationships and patterns. Large introductory science classes in universities as well as instructors' perceived need to prepare students for advanced coursework both in high school and at the university level have worked to maintain the transmission status quo of explain-apply pedagogy.

Instantiations of "scientific teaching" (Handelsman et al., 2004), on the other hand, include active participation in lectures and discovery-based laboratories that have been implemented and quantitatively evaluated in a variety of science courses throughout academia. Three well-developed methodologies that are based upon active student engagement with the subject matter include the *Learning Cycle Approach* (Karplus & Their, 1967), *Peer Instruction* (Mazur, 1996), and *Just-in-Time Teaching* (Novak et al., 1999).

The Learning Cycle Approach (Karplus & Their, 1967) was an outgrowth of the post-*Sputnik* reforms in elementary science education at a time when Piaget's developmental stages were interpreted by educators as constraints on what could be taught about science to young children. The approach emphasized exploration (concrete) before concept introduction (abstract) and application (use). This pedagogical development was somewhat serendipitous as it was motivated by what we now take as a misinterpretation of intellectual development. The active approach of the learning cycle in science instruction at the high school and college level in chemistry and biology has resulted in greater achievement and retention, improved reasoning ability, and superior process skills when compared to the traditional lecture approach (Abraham & Renner, 1986; Ebert-May, Brewer, & Allred, 1997).

Peer Instruction (PI) (Mazur, 1996) intersperses lectures with conceptual questions (*ConcepTests*) that are designed to expose difficulties students are having with understanding the material. In PI, students are asked to think for one or two minutes about the posed question and then formulate a written answer. They then spend three or four minutes discussing their answers with three or four neighbors and try to reach consensus through discussion. Students are engaged as they think through the various arguments presented by their peers. Instructors are able to formatively assess understanding of concepts in a timely fashion and thereby modify instruction to fit with the current knowledge state. Data from ten years of teaching both calculus-based and algebra-based introductory physics have shown increased student mastery of both conceptual reasoning and quantitative problem solving with the use of PI (Crouch & Mazur, 2001). To support PI for chemistry education, the University of Wisconsin maintains a website (http://www.jce.divched.org/JCEDLib/QBank/collection/ConcepTests) of ConcepTests for chemistry.

Just-in-Time Teaching (JiTT) (Novak et al., 1999) uses web–based preparatory assignments to engage students actively in learning before coming to lecture as well as to inform the instructor of their state of prior knowledge so that lectures can be adapted appropriately. The essence of JiTT is feedback. By reading students' submissions prior to class, faculty can adjust classroom lessons *just in time* to suit the students' needs. A comparison of traditional physics lecture courses with those that employ JiTT shows a 40% decrease in student attrition (dropout) rates as well as increased performance on the Force Concepts Inventory for the JiTT classes (Hake, 1998). Similar positive results have been documented for JiTT in biology, chemistry, and engineering courses (Marrs, Blake, & Gavrin, 2003; Marrs & Novak, 2004).

Lectures are not the only site available for transformation from a passive to active environment. Both laboratory and homework experiences also can present opportunities for helping the learner construct an integrated overview of the discipline under study. When cookbook-type labs are modified to reflect higher level intellectual demands such as hypothesis generation and testing with both individual and collaborative responsibilities, and when these open-ended inquiry experiences are integrated with, instead of detached from, lecture topics, the resulting conceptual change of the students is significantly greater than that of students from a traditional course (Udovic, Morris, Dickman, Postlethwait, & Wetherwax, 2002). When open-ended homework assignments in which students interact with web-based simulations to solve real-world problems replace some of the standard back-of-the-book exercises, learning outcomes are no longer highly correlated to students' prior experience with the material (Cuadros, Leinhardt, & Yaron, 2007).

Schema acquisition and automation are facilitated by instructional strategies that promote active engagement rather than passive absorption. Methodologies such as the Learning Cycle

Approach, Peer Instruction, Just-in-Time Teaching, and open-ended inquiry labs and homework assignments have increased student performance in science courses. Yet students' cognitive architecture also has significant implications for instructional design.

2.2.2 Cognitive structure

The fact that humans have limited processing space should be considered when designing instruction so that cognitive overload does not interfere with learning. Traditional instruction that follows the explain-apply format may actually contribute to cognitive overload when students are asked to solve novel practice problems for which they have not yet developed schemas that chunk and/or automatize the multiple elements needed for the generation of solutions. Stoichiometry problems that rely on symbolic representations of abstract entities which give rise to macroscopic measurements are classic examples of this potential for cognitive overload. Although a means-end strategy may result eventually in a solution for a particular problem, the need for repeated extraction of differences between problem state and goal state during problem solving along with the search for operators to reduce or eliminate those differences far exceeds the cognitive capacity of novices. Therefore, these actions do not promote the development of schemas let alone their smooth, quick, and effortless execution during problem solving--important goals of the learning process (Sweller, 1994). Yet frequent practice with problems germane to a domain is necessary for the consolidation and restructuring of schemas in the manner of domain experts (Anderson, 1993).

Zhu & Simon (1987) actively engaged students by having them study worked examples of algebra problems and then solve practice exercises. Protocol analysis revealed that students did not work mechanically from the examples to the exercises but rather extracted appropriate principles from studying the examples that guided their solutions to the practice exercises. Using the method of learning from examples, students were able to complete a three-year mathematics course in two years. High performance on a retention test one year later supported the hypothesis that the learning was not only efficient but also meaningful. In a serendipitous manner, active engagement with worked examples can also reduce cognitive load since the learner needs to attend only to each step (or problem state) and the specific move needed for transformation to the next step.

A comparison of students learning geometry from worked examples combined with practice problems versus only from practice problems found that those students in the worked examples group learned faster, scored higher on a test with similar problems, and outscored the traditional problem-solving group on transfer problems that required application of the principles that had been taught (Paas, 1992). Trafton & Reiser (1993) determined that alternating worked examples and practice problems was an effective way to facilitate learning since having a similar problem (worked example) immediately available in memory supported its application to a new problem. Together these findings support the hypothesis that actively studying worked examples is superior to traditional problem-solving practice for schema acquisition.

The use of worked examples and practice problems does not guarantee the construction of a well-integrated knowledge base. It is the active engagement with the worked examples through reflective consideration of the solution process rationale that serves to connect new information to learners' existing knowledge in long-term memory. Students who self-explain worked examples learn more than those who tend to them in a more cursory manner (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). Since most students do not spontaneously provide effective self-explanations when studying worked examples, instruction should provide prompts for eliciting them so that the freed processing capacity is effectively used (Renkl, 1997; Renkl, Stark, Gruber, & Mandl, 1998). Self-explanation of worked examples has been shown to be beneficial in initial skill acquisition but practice with solving problems is necessary to develop fluidity and accuracy. Therefore, after an initial knowledge base has been developed through self-explaining worked examples, support should be faded gradually from the use of incompletely worked examples to independent problem solving. Renkl & Atkinson (2003) have found that a backward fading process (starting with last step of a worked example's solution) along with prompts for self-explanations did not result in cognitive overload and fostered both near- and far-transfer performance.

Skills that are practiced are skills that are learned even if what is learned is in error and not the specified goal of instruction (Lovett & Greenhouse, 2000). Therefore, feedback is an important tool in instructional design. The exceptional learning gains documented from studying with human tutors have been attributed to the rich and timely feedback that they give (Bloom, 1984). Although rare, delayed, and usually occurring as part of a summative evaluation in most traditional classrooms, feedback can formatively enhance learning through a complex interaction of its timing, its specificity, and the type of learner responses. Most research findings point to the value of feedback that is immediate, verifies whether a response is correct or incorrect, and provides cues to guide the learner in formulating a correct solution (Kulik & Kulik, 1988; Mason & Bruning, 2001).

Although many of these instructional applications were developed in appreciation of students' limited capacities for processing new information during their learning process, the availability of both auditory and visual information channels may enable a greater number of chunks to be effectively processed. Research findings from instantiations of this multimedia principle have suggested that appropriately designed web instruction is superior to traditional text-based formats (Clark & Mayer, 2003).

2.2.3 Context

One of the critical tasks of chemistry instruction is the transformation of the domain's knowledge for learning. In the service of this goal, instructional explanations function to clarify and connect concepts with procedures and thereby help learners develop and use their acquired knowledge in flexible ways during problem solving. Instructional explanations model the types of questions posed in a domain such as chemistry as well as model the ways in which these queries are answered (Leinhardt, 2001). Instructional explanations are important since doing them well promotes learning and doing them poorly interferes with learning (Eisenhart et al., 1993). Therefore, the design of instructional explanations, whether published in a textbook, facilitated by a classroom teacher, or delivered online, should reflect a practice informed by research.

The context-dependent nature of cognition suggests that for newly learned knowledge to be functional it needs to be processed within its authentic context of use. Practice with hitting stationary balls at a driving range may effectively improve your golf score, but it does not transfer to returning a slice serve on the tennis court. Likewise, trying to teach students to use general, context-independent cognitive strategies has no clear benefits outside of the specific domains in which those strategies are taught (Pressley, Snyder, & Cariglia-Bull, 1987). As concrete instantiations of abstract concepts, examples serve as core components of instructional explanations. Examples can introduce a concept by allowing learners to connect their prior knowledge with the new information, can function as boundaries of concepts, can serve as templates for organizing domain knowledge, and can afford the bases for inductive generalization (Rissland, 1991). For newly learned concepts and procedures to be flexible—that is, able to be applied to multiple situations within the domain of study--students need experience with multiple and variable examples in different contexts from which they can extract the critical underlying principle(s) (Perkins & Salomon, 1989; Quilici & Mayer, 1996). The resultant multiple encodings serve to strengthen a given problem schema resulting in more generally applicable knowledge and skills (Paas & Van Merrienboer, 1991; Ranzijin, 1991).

Analogies are another explanatory tool that can be used to familiarize learners with new information. An analogy compares similar features of two concepts, one familiar and one unfamiliar, as opposed to an example that is a concrete instance of a given unfamiliar concept. When more than one example is used as part of an instructional explanation, however, the association between them and the given concept includes comparisons. By portraying the underlying principle of the concept, these examples stand in an analogical relation.

Research on the instructional use of analogies has shown that visualization of abstract principles can be facilitated by pointing out similarities in the real world through consideration of students' prior knowledge. However, since an analogy is never an exact fit, differing features between the target (unfamiliar concept) and the analog (familiar concept) can mislead. For example, Gentner and Gentner (1983) found that two different analogies for electric current produced different performances by the students exposed to them. Students presented with a flowing waters analogy did better on battery problems whereas those presented with a teeming crowds analogy did better on resistor problems. The specificity of support by these analogies suggests the need for multiple analogies during instructional explanations to avoid the possibility of analogy-induced misconceptions (Spiro, Feltovich, Coulson, & Anderson, 1989).

Although students may access analogies by surface similarities of the target and analog, it is only the deep structural aspects that have inferential power (Duit, 1991). The successful use of analogies in learning situations has been shown to require considerable guidance (Gick & Holyoak, 1980). Instructor-designed analogies for stoichiometry problem solving are more effective for students of lower formal reasoning ability than for more capable students (Gabel & Sherwood, 1980). Working in the same content area, Sutala and Krajcik (1988) found that students with high cognitive abilities benefited more from creating their own analogical connections whereas students with lower abilities benefited more from having the teacher make them.

2.2.4 Summary

Pedagogical methodologies that encourage the active engagement of the learner, consider the learner's cognitive structure, and provide multiple encoding opportunities for the development of a flexible knowledge base have been shown to be effective tools for promoting the meaningful stoichiometry learning needed for application to problem solving in equilibrium and acid-base chemistry. The instructional and learning challenges of the stoichiometry toolbox are ones that online technology may be equipped to address. A multimedia platform, which includes interactive simulations by which the invisible can be made visible as well as provisions for scaffolding of, and timely feedback for, student problem solving, should be able to support learning in a complex and abstract domain such as chemistry.

2.3 USING ONLINE TECHNOLOGY TO DELIVER INSTRUCTION

Online technology as a medium for instructional delivery can support the learning and/or review of stoichiometry concepts and procedures. The rapid expansion of the Internet across regional, social, and technological barriers now provides the accessibility, convenience, flexibility, and affordability of the World Wide Web's vast library of resources to enhance the quality, individualization, and egalitarianism of instruction. Recent advances in multimedia and communications technology enable levels of interactivity and knowledge construction unencumbered by time and location constraints, a feature particularly amenable to personal review of previously learned content such as stoichiometry. These technological tools can create the interactions (e.g., simulations, feedback, explanations, etc.) that may enhance learners' construction of their knowledge frameworks. But it is the findings from research on learning, whether facilitated by technology or not, that must guide the development of online learning environments. For example, to learn from a simulation, the students must understand what they should accomplish and must be scaffolded and coached appropriately in achieving their goals. An informed instructional design can individualize online courseware in a way that optimizes the development of a fluid and flexible stoichiometry framework for learners independent of their level of prior knowledge. Three features of online technology that have been shown to support meaningful learning are dynamic explanations through multimedia, supported practice opportunities with feedback, and simulations for developing inquiry.

2.3.1 Multimedia to facilitate dynamic explanations

The Multimedia Principle asserts that instruction that incorporates words and graphics encourages learners to engage in active learning by making connections between the verbal and pictorial representations (Clark & Mayer, 2003). In contrast, using only text-based instruction may encourage shallow learning in that learners may not actively connect words to their other knowledge. Explication of stoichiometric procedures using videos accompanied by voice over narration allows the explanations to include not only the *how* but also the *why* of the procedures. Furthermore, a multimedia format allows learners to employ both their visual and auditory channels in processing new information and perhaps avoid cognitive overload (Moreno & Mayer, 2000; Sweller, 1994). Learning to move effortlessly within the complex tripartite structure of chemistry (macroscopic, submicroscopic, symbolic) can be facilitated by dynamic simulations that point out relationships among these three levels both visually and verbally. Obviously, a multimedia format facilitates learning *only* if the target of the effort is the difficult part of what is to be learned.

2.3.2 Tutorials to facilitate fluency from interactive practice

Development of expertise is strongly related to practice. In the information-processing model of knowledge acquisition, practice affords opportunities for integration of new knowledge into the learners' cognitive frameworks. The more that learners practice (up to a point), the better they get at problem solving, regardless of initial talent and ability (Ericsson & Charness, 1994); the more encoding opportunities that are accessed, the more connections that are made, resulting in a greater probability of retrieving the new knowledge when needed for subsequent problem-solving situations. Variations in practice opportunities can be provided in online environments through parameterized problems in which the learner continues to practice a specific procedure until fluency is achieved. Online technology can enhance practice opportunities by incorporating immediate feedback in the form of hints and confirmations not unlike those interactions with a human tutor that have been shown to result in significant learning gains (Bloom, 1984).

2.3.3 Simulations to facilitate inquiry

The body of definitional knowledge that students acquire through expository explain-apply regimens is often inert--unusable out of the context in which it was taught, namely within the carefully organized structure and content of classroom notes. The ability to both understand and develop solutions to complex problems requires an intuitive knowledge base. This knowledge base may best be developed through the practice of authentic inquiry activities that require the planning and executing of experiments as well as interpretation of data. Authentic activity in chemistry is often too dangerous, too time consuming, or too obscured by the interaction of multiple variables to be of cognitive value to the learner. Furthermore, without the practiced kinesthetic skills needed for laboratory work, the quality of data from which inferences are made is questionable. Multimedia technology has been able to use mathematical or logical algorithms to reproduce selected characteristics of chemical systems such that the effect of changing individual variables' values can be observed (Pence, 1997). Such a feature of online technology can provide an instructional tool that enables chemical systems to be explored rapidly and effectively. Without the challenges and obstacles of working in a natural environment, students' interactions with simulations may promote the development of the intuitive knowledge base needed for complex problem solving.

The design of a simulation may be *stripped down* to highlight only those variables directly involved with a given concept or procedure. For example, a simulation of limiting reagents, a difficult but necessary stoichiometry concept needed for success in freshman college chemistry, may focus only on a graphical representation of changing amounts of substances in a chemical equation. Such a simulation may support initial concept development of limiting reagents. A more complex simulation may incorporate a virtual laboratory with glassware, instrumentation, and solutions to use in the service of solving authentic problems such as removing arsenic from a water supply. Such a simulation can provide multiple encoding opportunities for more advanced learners, a process that aids in the development of an intuitive understanding of chemical processes.

A review of research studies that have evaluated learning from simulations shows that without instructional support gains are often unclear, disappointing, or both. Students who are unfamiliar with a domain benefit from program-controlled, sequenced assignments when first interacting with a simulation (Swaak & De Jong, in press). On the other hand, students who are familiar with the domain at hand (such as in a review course for stoichiometry) are better served by learner-controlled support provided through a series of hints that may remind them of the goal of the activity and give some general advice on how to approach a solution (Clark & Mayer, 2003).

2.3.4 Summary

A decade ago Osin and Lesgold (1996) proposed that intelligent computer systems coupled with domain simulations might facilitate a cognitive apprenticeship model of learning by which novices (students) are supported by experts (in this case, the computer) as they solve authentic, albeit difficult, tasks in the process of developing competency in the domain. The distinctive features of online instruction include abilities to dynamically explicate abstract information, to provide timely feedback for practice, and to scaffold the execution of complex tasks so that learners focus on knowledge relationships rather than individual bits of information. These interactive opportunities support a constructivist environment through active engagement of the learners in revision of and building on their current understandings through exploration and reflection. The development of a stoichiometry course that uses online technology to support cognitively informed instruction that provides dynamic explanations along with coached and scaffolded practice with interactive simulations in the service of authentic problem solving is described in the Methods section. Such a course may enhance subsequent instruction in chemistry by moving the topic of stoichiometry from being a collection of tools (Evans et al., 2006) to being tools in use. It was chosen for this study after careful analysis of several online candidate courses.

2.4 REVIEW OF ONLINE CHEMISTRY COURSES

The need for students' independent review of stoichiometry concepts and procedures in an introductory college chemistry course precipitated a search for online instructional resources. This search was conducted on the World Wide Web because of its accessibility to individual learners as well as the its potential for dynamic and interactive instruction. The search investigated courseware that integrated and applied tested theories of learning from information-processing, sociocultural, and behavioral perspectives. The search looked for coursework that was grounded in a cognitive analysis of the domain and that promoted schema construction.

Another goal of the search was to find courses whose instructional materials reflected a sociocultural understanding of the practices of chemistry—that is, teaching how chemists use the tools of the domain rather than teaching the tools in isolation. Finally courses were examined for their incorporation of feedback and fading in support of knowledge development. A complete report of this review of online chemistry courses is located in Appendix A. Included in this section is a summary of the methods and results of the analysis.

2.4.1 The courses

The five courses that were selected for review came from a variety of sources, such as course websites or commercial ventures (e.g., textbook companion websites and stand-alone CD-ROM courses). Each of the following sets of online materials was accessible through either a MAC or a PC platform, addressed the conceptually difficult stoichiometry competences necessary for success in subsequent coursework, provided explanations of content with worked examples of procedures and practice tasks, and was amenable to self-study without the intervention of an instructor.

1. OSU: *Grandinetti's General Chemistry Lectures* (http://www.chemistry.ohio-state.edu/~grandinetti/teaching/Chem121/lectures/)

2. NORTON: *Student website for Chemistry: The Science in Context* (http://www.wwnorton.com/chemistry/home.htm)

3. THINKWELL: *Thinkwell Chemistry* (www.thinkwell.com)

4. GENCHEM: *General Chemistry Interactive* CD-ROM, Version 3.0 (ISBN: 0-03-035319-X)

5. OLI: *Open Learning Initiative Chemistry* (http://www.cmu.edu/oli/courses/enter_chemistry.html)

2.4.2 Analysis

In each course the same three stoichiometry target topics were selected for review based upon their disciplinary applications in equilibrium and acid-base chemistry as well as their conceptual difficulty for beginning chemistry students: limiting reagents, molarity, and dilution. Course segments corresponding to these topics were analyzed in terms of the quality and quantity of *examples* and *tasks*, as well as the pedagogical implementation of *online resources* (e.g., dynamic representations and interactive opportunities).

2.4.2.1 Examples For the purpose of this analysis, an example was defined as a specific illustration of a concept or a procedure. The quality of examples examined ranged in cognitive demand from the cursory application of a procedure to its authentic use in a real-world scenario. Five types of examples were identified as either cognitively simple or cognitively complex. The number of different examples for each target topic in each course was counted in order to determine whether students would have sufficient opportunity to distinguish relevant from incidental features of specific problem types. For each course the total number of each type of example across the three target topics also was tabulated. Since both the quality and quantity of examples are important conditions for learning from them, each course was ranked according to both criteria. A complexity index was calculated based upon the proportion of each course's total number of examples that were identified as cognitively complex (i.e., demanding). For each course the mean number of examples across topics was plotted against this complexity index.

2.4.2.2 Tasks For the purpose of this analysis, a task was defined as a specific activity that must be completed by the learner in the service of practice and/or knowledge assessment. The quality of tasks ranged in cognitive demand from the simple recall of facts or definitions to real-world problems with no defined solution path. Five types of tasks were identified as either cognitively simple or cognitively complex. Multiple practice opportunities that address a range of situations have been shown to be necessary for improved performance in problem solving by promoting efficiency and proficiency (Clark & Mayer, 2003; Rosenbaum, Carlson, & Gilmore, 2001). Therefore, the number of different tasks for each target topic was counted. For each course the total number of each type of task across the three target topics was also tabulated. Since both the quality and quantity of tasks are important conditions for learning from them, each course was ranked according to both criteria. Complex tasks provide more opportunities for engagement and encoding than simple recall or procedural tasks. Therefore a complexity index was calculated based upon the proportion of each course's tasks that were identified as cognitively complex (e.g., exhibited complex procedures, conceptual reasoning, or authentic problem solving). For each course the mean number of tasks across topics was plotted against this complexity index.

2.4.2.3 Online resources A distinctive feature of online technology is the ability to provide dynamic explication of abstract information and interactive opportunities to support exploration and reflection by learners in the service of revising and building upon current levels of understanding. An estimation of the level of pedagogical implementation of online resources among the selected courses was made: by counting the different types of dynamic and interactive learning objects; by identifying the location, control, and type of feedback opportunities; by comparing the types of scaffolded practice in problem solving; and by evaluating the use of simulations as exploratory learning objects.

2.4.3 Results

Of the five courses analyzed the OLI course provides the highest degree of cognitive complexity among examples and tasks. More than 70% of both its examples and its tasks are of an authentic problem-solving or conceptual nature. The availability of these cognitively demanding instructional aids in the OLI course can provide the learner with more opportunities for engagement and encoding than can those examples or tasks that are of a simple procedural nature. OLI's actual number of examples and tasks, however, is the lowest (less than two examples and five tasks per topic) among all the courses reviewed. This low number of examples and tasks may not be sufficient to promote the deep processing needed for developing the flexibility and fluency required for intuiting solutions to equilibrium and acid-base problems. The other courses offer more examples and tasks (up to an average of six examples and nine tasks per topic per course). Yet less than 50% (and as few as 10%) of the examples and tasks in those courses are of an authentic or conceptual nature, emphasizing instead the execution of simple procedures.

The interactive learning objects made available by the various courses that were examined range from simply providing quiz results to providing rich virtual environments that can be explored. OSU offers a single type of dynamic learning object, specifically quizzes with feedback. NORTON, THINKWELL, and GENCHEM support students in complex problem solving by relieving them of hand computations through applets that automatically calculate quantities such as molar mass from chemical formulas. These three courses also centralize needed atomic data within an interactive periodic table. NORTON, GENCHEM, and OLI offer tutorial objects that incorporate both feedback and coaching in the service of developing student proficiency with specific, albeit simple, procedures. Only GENCHEM and OLI provide exploratory environments in which students can freely change parameters and note the systemic changes. Coordination of these two activities may promote development of conceptual connections between two or more of the different levels (macroscopic, submicroscopic, and symbolic) of the domain's structure.

Just as the complexity and frequency of examples and tasks vary among the courses, so to do the pedagogical affordances of the interactive learning objects (e.g., tutorials and simulations) vary. Tutorials across the three courses that offer them (NORTON, GENCHEM, OLI) all provide feedback in the form of hints and confirmations. The tasks in NORTON's and GENCHEM's tutorials are predominantly of a simple procedural nature that function as exercises in algebraic manipulations, albeit with vocabulary and variables rooted in chemistry. The OLI tutorial design, however, situates the algebraic manipulations of stoichiometry in the context of a real-world use for analytical chemistry. Such a tutorial located in an authentic practice of chemistry may both promote efficiency with the algebraic procedures as well as foster the development of a conceptual understanding by encoding knowledge in use.

GENCHEM and OLI are the only two courses examined that provide simulated environments as interactive learning objects. Both of the courses' simulations allow for exploratory actions by the student in addition to the courses' stipulated tasks. GENCHEM's simulations superimpose an ordering of actions for the learner, accompanied by confirmatory and procedural feedback, within a basic symbolic interface. The simulated reality of OLI's Virtual Lab allows learner-imposed sequencing of actions that are scaffolded through generalized hints and goal reminders. Since the OLI course was developed specifically as a stoichiometry review, the content would be somewhat familiar to the users and therefore this less-structured approach to working with the simulation is appropriate (Swaak & De Jong, in press).

2.4.4 Conclusions

GENCHEM and OLI are two courses examined that provide cognitively informed instruction and that pedagogically implement the dynamic and interactive features of online technology. The other courses (OSU, NORTON, THINKWELL), although content valid, appear to be lacking significant input to their design from application of theories of learning or pedagogical implementation of online affordances. OSU is essentially a compilation of a professor's lecture notes delivered online as text. There are no visualizations or interactions except navigating throughout the website and responding to quiz questions. THINKWELL consists of videotaped lectures with colorful visuals and supplementary notes as downloadable PDF files. Opportunities for interaction are limited to responding to quiz questions and navigating throughout the program. NORTON provides rudimentary tutorials with minimal scaffolding as well as multiple examples and tasks, yet the majority are cognitively simple in nature with no instantiations of authentic problem solving.

Each course, other than OLI, treats the topic of stoichiometry as an end to itself rather than a tool in use. This approach to chemistry in which the domain is decomposed into a multitude of skills to be mastered before *getting to the good stuff*, is characteristic of the traditional chemistry curriculum with its attendant problems for memorable learning (Evans et al., 2006). Introductory college chemistry students who have previously studied stoichiometry within the context of a traditional chemistry curriculum, for example, have difficulty intuiting its use in the context of equilibrium and acid-base problem solving (D. Yaron, personal communication, May 19, 2004). OLI situates stoichiometry instruction within the context of an analytical problem, the measurement and remediation of arsenic in groundwater. This design principle of an overarching real-world story to model chemistry in use may serve to both motivate learners and support their integration of knowledge.

In addition to the real-world context, the OLI course incorporates design principles based upon the findings from both the cognitive and behavioral perspectives of learning research: the use of an exploratory virtual laboratory in support of conceptualizing and practicing competencies; the relevance of a variety practice contexts; the importance of a variety of feedback experiences as students practice problems, from being able to track the effects of certain actions to getting responses to their submitted answers. In addition, the course works from a principle of explanation and example-based learning. For these reasons OLI was chosen as the technology-rich treatment for this investigation.

3.0 METHODS

In this chapter the design of the materials and methods of data collection and analysis used in this study are described. The first section describes the purpose for studying alternative delivery formats for learning stoichiometry by entering university freshmen. The second section describes the design of the study with special detail given to the motivation for, and process of, development of the treatment conditions and assessment instruments. The third section describes how the data were analyzed in the service of answering each of the research questions.

3.1 PURPOSE OF THE STUDY

The purpose of this study was to try to understand the nature of learning stoichiometry by entering university freshmen who plan to pursue science or engineering degrees. Although stoichiometry is addressed in most high school courses, college instructors have noticed that students do not seem to be able to make flexible, fluid, and accurate use of this central tool for chemistry work even if the content is reviewed early during a freshman chemistry course by direct instruction or self-study. Even science majors find the notational and mathematical reasoning features of stoichiometry challenging to master using traditional text-based materials. Perhaps the affordances of online technology could reduce the effort required to learn stoichiometry concepts and procedures. Therefore, this research endeavor was undertaken to answer four questions about learning stoichiometry with regard to the design and delivery of its instruction as well as the influence of student background characteristic and study practices:

1. To what extent does receiving instruction in a technology-rich learning environment that incorporates a dynamic interface, timely and informative feedback, and an overarching storyline, influence the learning of stoichiometry?
2. How are background experiences and characteristics related to the learning of stoichiometry?
    a. How is the degree of prior knowledge of math and chemistry related to the learning of stoichiometry?
    b. How is the demographic of gender related to the learning of stoichiometry?
3. To what extent do a technology-rich environment and student background experiences and characteristics work together to influence the learning of stoichiometry?
4. How are learning practices that are facilitated by a technology-rich environment related to the learning of stoichiometry?

Specifically, the goal of this research was to ascertain whether the affordances of dynamic and interactive online technology along with an overarching real-world story would promote stoichiometry learning to a greater degree than a static, text-only format that provided the same content and utilized the same cognitively informed pedagogical principles. Learning was assessed by student performance on posttests designed to measure the attainment of the stoichiometry competencies necessary for success in the second semester introductory chemistry course.

3.2 DESIGN OF THE STUDY

The study design was a random assignment of entering volunteer students from Carnegie Mellon University (CMU) to either a dynamic and interactive online course or a text-only set of guided self-study course materials before the students arrived on campus for the 2005 Freshman Orientation Week in late August. The entire study took place during the last week in July and the first three weeks of August, 2005, sometime after students had graduated from high school but before they began their university courses. This timing was important for several reasons. First, the content addressed by the study materials would be helpful as a review and/or preparation for forthcoming college coursework. Second, the students were recruited by individual emails in locations distributed across a large geographic area, a practice that lowered the probability of introducing a student-student interaction variable had they already been on campus. Finally, by offering the study toward the end of summer when students were not enrolled in other classes but were likely finished with vacation travel, there was a greater chance that students would have time to complete the materials than they would have had were they already on campus, since the students had approximately three weeks before the start of school to cover about 20-30 hours of instruction on their own. Upon completion of either the dynamic and interactive course or the text-only materials, students completed an online test (posttest-1) followed by an in-person exam on campus (posttest-2) on the same material approximately five days later. A subset of the participating students completed a follow-up exam (posttest-3) five months later during the first class of the second semester introductory chemistry course.

3.2.1 Population

Volunteers, who were at least 18 years of age and whose residences were identified as being in the United States, were solicited by email from the 2005 incoming CMU freshman class. Email solicitations were limited to students identified with the Mellon College of Science (MCS) and the Carnegie Institute of Technology (CIT) because the vast majority of CMU students who study introductory chemistry are registered in those colleges. Students whose residences were not identified as being in the United States were excluded because of the strong chance of computer incompatibility.

Students were solicited by email with a promise of payment ($50) and the possibility of placing out of a required test of stoichiometric knowledge (Appendix B). A total of 426 students were contacted. Seventy students initially responded positively; 50 students started one of the two courses and 45 completed one of the two treatment conditions. The sample of 45 students included 27 males and 18 females. First semester introductory chemistry courses at CMU require that students pass a mastery examination on stoichiometric problem solving. Students are not taught the material and are expected to self-review for this examination since the faculty considers the material to have been previously addressed by the high school chemistry curriculum. In the past students were found to need up to six tries on the mastery test to pass it; the majority of students fail the first attempt (D. Yaron, personal communication, May 19, 2004). Participants in this study were permitted to use a passing grade on the study's proctored posttest as evidence of mastery of the required stoichiometric problem solving skills for first semester introductory chemistry. Upon completion of the materials and the posttests, volunteers were reimbursed 50 dollars.

3.2.2 Treatments

There were two treatment conditions in the study. Each addressed the same specific stoichiometry topics that undergird the aqueous solution equilibrium principles and procedures introduced during a second semester introductory college chemistry course:

- Assigning and identifying the number of significant figures
- Using dimensional analysis to convert units of measurement
- Calculating molecular weight
- Using the mole and molecular weight to mathematically convert between the macroscopic and molecular world
- Identifying mole relationships in chemical formulas
- Determining the percent composition of a compound from its formula
- Using molarity to express the concentration of a solution
- Calculating molarity of diluted solutions
- Determining the empirical formula of a compound from its molecular formula
- Determining the empirical formula of a compound from its mass composition
- Using stoichiometric ratios in reactions to determine the mass amounts of reactants needed
- Calculating the theoretical and percent yield of reactions
- Identifying the limiting reagent in a chemical reaction
- Using titration to determine solution concentration
- Analyzing the composition of mixtures using stoichiometric ratios of reactions

Each treatment condition also was designed for students who had completed a high school chemistry course and were familiar with chemical formula notation such as H_2O and with chemical reaction notation such as $2Mg + O_2 \rightarrow 2MgO$. Students were expected to have heard of the *mole* but not to fully understand its utility in quantitative chemistry activities.

3.2.2.1 Dynamic and interactive treatment The motivation for development of this treatment condition was that college chemistry faculty both at CMU and other institutions have found that students regularly are unable to use stoichiometric routines and procedures with flexibility and skill. Since stoichiometry is an important base of knowledge for introductory college chemistry, lack of competence with its concepts and procedures remains a barrier to success for many students throughout the first year introductory course. An online course may be a useful way to provide an opportunity for students to learn the material before or during the early portion of a college chemistry course. With support from the William and Flora Hewlett Foundation through the Open Learning Initiative (OLI) at CMU, a collaborative team of content area experts, educational psychologists, instructional designers, and multimedia specialists developed an online stoichiometry review course based upon the following design principles: a belief in the power of an overarching real-world story or context to both motivate and integrate ideas; the use of an exploratory virtual laboratory in support of conceptualizing and practicing competencies; the relevance of a variety of practice contexts; the importance of a variety of feedback experiences as students practice problems, from being able to track the effects of certain actions to getting responses to their submitted answers. In addition, the course works from a principle of explanation and example-based learning.

The cover story that was chosen as the real world context for this online course was arsenic contamination of the drinking water in Bangladesh. The amount of arsenic present in ground water is an issue that suggests problems that get to the heart of stoichiometry. The contextual setting of groundwater contamination operates at the macroscopic (e.g., concrete, tangible) level from which interpretations can be made at the submicroscopic level and then recorded using symbolic notation. By embedding stoichiometric knowledge in a real-world setting that highlights its utility, students can learn and practice concepts in an appropriate context and thus establish a coherent cognitive framework.

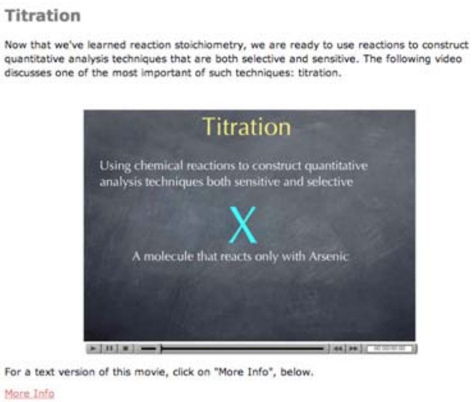
A second design principle was the use of the Virtual Laboratory simulation that provides a manipulative and exploratory environment that enables a new type of interaction with chemical phenomena (Yaron, Freeland, Lange, Karabinos, Milton, & Belford, 2001). The Virtual Lab supports the connection of mathematical procedures and representations of stoichiometry to the macroscopic context of authentic chemistry. Unlike a physical laboratory in which students can *see* only the macroscopic results of chemical interactions, the Virtual Lab additionally provides a simultaneous quantitative representation of the abstract and invisible chemical species present. These responsive representations serve to link mathematical computations and actual chemical phenomena during problem solving and thereby promote development of a flexible knowledge base.

A third design principle was the use of feedback with practice exercises. Feedback supports learning by providing opportunities for revision and improvement of students' thinking. The stoichiometry review course provides several levels of immediate feedback in response to student interactions with the course. In addition to feedback about responses being correct or incorrect, cognitive support in the form of hints and step-by-step tutorials encourages the formation of explicit connections between a student's existing knowledge state and new information. The interactive nature of an online delivery system facilitates the immediate and structural feature of the feedback available in the technology-rich OLI course.

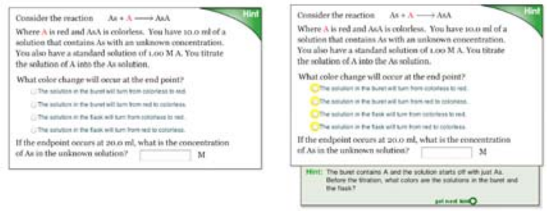
For each learning module of material there is a thorough explanation of stoichiometric tasks as well as the procedures by which these tasks can be accomplished. The description is multimedia based and supports both a sequence of steps and their rationale.

The course is divided into two units, each with multiple modules. A drop-down syllabus allows students to navigate to any module at will. Within each module are *previous* and *next* buttons for linear navigation throughout the program. The first unit develops the context of arsenic contamination, explains the use of the Virtual Lab and other interactive features, reviews basic measurement skills, and addresses basic compound and solution stoichiometry. The second unit develops the use of stoichiometric tools within chemical reaction analysis. The course requires an estimated 20-25 hours to complete. Most topics are described via voice-over video explanations or animations. An optional text-only format also is available. Movies and still pictures of the context (Bangladesh: geography, people, water supply) are interspersed throughout the course in the service of explicating certain stoichiometric concepts. Following each topic presentation are practice questions and problems, all of which provide immediate feedback and hints at the student's request. Practice exercises are provided in various formats, including multiple choice, short answer, and extended response from Virtual Lab activities. Online tutors help students learn the more complex stoichiometric calculations. Parameterization of these tutors provides a variety of instances comparable to the variation found among the end-of-chapter problems in a textbook. Each of the two units ends with a recap module for review of, reflection upon, and extension of, the concepts addressed. The course was accessed through a secure website.

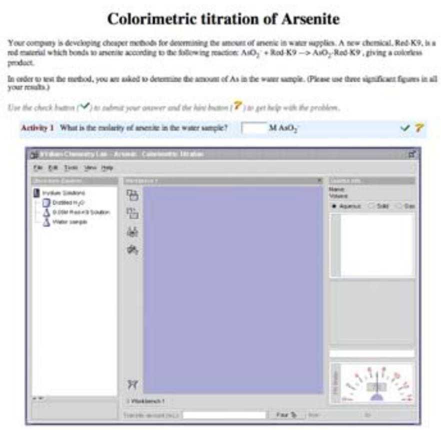
As an example of the content and context provided by the OLI course, Figure 1 illustrates through screenshots the multiple dynamic learning objects available to the student in the *Titration Module* located in the second unit of the course. It is this unit that develops the use of stoichiometric tools within the real-world application of chemical reaction analysis. Titration is an example of a quantitative analysis technique that is explained in the context of efficiently, effectively, and inexpensively determining the amount of arsenic in the water supply. Figure 1(A) depicts a voiceover movie that includes a thorough explanation of the titration procedure as it used to accomplish a real-world task. Beneath the screen is a link to a text version of the same lesson. Figure 1(B) shows one of the interactive questions that immediately follow the titration lesson. This type of question provides hints (from 3-6 per response) to guide a student through a calculation, with the last hint being a bottom-out hint that provides the answer. Figure 1(C) is a collection of four screen shots from a parameterized tutor within the Virtual Lab. The student is given the opportunity to first solve the problem (C-1), for which hints and feedback that check for common errors are provided (C-2). Students may request the tutor mode, which assists them by providing sub-goals to be solved in a step-by-step fashion. Hints and feedback are available for each sub-goal if requested by the student.

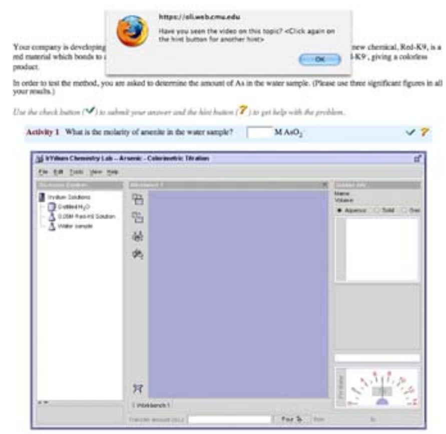


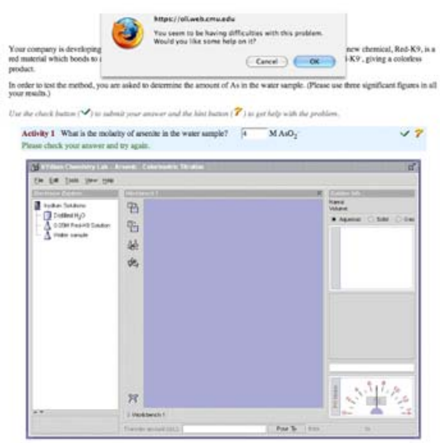
(A) Multimedia explanation with "more info" link to text version.



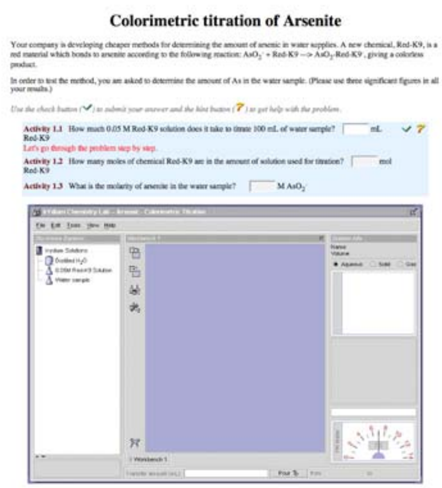
(B) Practice question with hint request/response.







(C-3)



(C-4)

(C) "Learn by doing" problem using the Virtual Lab that incorporates feedback and a tutor mode.

Figure 1: Screenshots of Titration Module activities from Unit 2 of the OLI course. See text for detail.

3.2.2.2 Static text-only treatment This treatment condition was designed as a study guide for reviewing the same stoichiometry content as that addressed by the dynamic and interactive treatment condition of the technology-rich OLI course. It incorporated pedagogical principles in text-only format that were adequate for content presentation and review. Each lesson included a brief explanation in the direct service of a specific problem type, a worked example problem with all moves explained as to purpose, a worked example problem with no explanation, and three practice problems for which no solutions (feedback) were available. The format of these materials was similar to that found in a textbook, except that in a textbook not all the topics addressed by the OLI course would be found as a cohesive unit. By developing text-like contrast materials, identical content would be accessed by participants from both treatment conditions. If performance differences were found between the two groups, they could be attributed to the design principles and their execution (context, dynamics, feedback), not to the content. This static, text-only study guide was an improvement over the traditional practice at CMU that consisted of posting problems to be learned and providing testing situations.

The text-only, self-study guide is composed of sixteen lessons that mirror the topics in the technology-rich course. Each lesson is designed in the same way and incorporates the aforementioned pedagogical principles. Students can skip sections but there are no branches to other topics. There is no overarching cover story to provide connections among the topics or instantiations of stoichiometric knowledge in real-world use. There are no dynamic learning objects such as multimedia explanations, exploratory simulations, or feedback. The complete study guide was posted as a PDF file on a secure website.

Figure 2 shows the titration lesson from the self-study guide as an example of the instructional design used in the static, text-only condition. This lesson addresses the same content as the *Titration Module* found in the second unit of the OLI course and illustrated in Figure 1. First the student reads a brief description of the topic. Then an example problem is presented (*Explained Problem*). When possible, as in the case of this lesson on titration, the most difficult problem from the parallel OLI module is used as a worked example in which both condition and action descriptions are presented. This worked example is followed by another worked problem in which only actions are shown (*Worked Example*). Finally, three practice problems (*Practice Problems*) are presented for the students to solve. Whenever possible, the example and practice problems that were used in the text-only condition were drawn from the OLI course. The study guide was developed by the author of this dissertation and was reviewed by content experts for accuracy.

STOICHIOMETRIC APPLICATION – TITRATION

EXPLAINED PROBLEM

Titration is an application of the stoichiometric toolbox that chemists use to quantify solutions of unknown concentrations. These tools include stoichiometric ratios of reactants, limiting reactants, composition stoichiometry, creating solutions, and dilution. Titration, or volumetric analysis, is used to determine the concentration of a solution by using a chemical reaction of known stoichiometry. Many titrations use color change as an indicator of reaction completion.

Your company is developing cheaper methods for determining the amount of arsenic (As) in water supplies. RED-K9 is a red material that bonds to arsenite according to the following reaction that produces a colorless product: $AsO_2^- + \text{RED-K9} \rightarrow AsO_2\text{-RED-K9}^-$. You have been given a 100.0-mL water sample and asked to determine the concentration of arsenic (As) in the water. You add a 0.050 M RED-K9 solution drop by drop to the water sample until the red color of the RED-K9 remains. This endpoint of the titration occurs when 44.56 mL of 0.050 M RED-K9 is added. What is the concentration of arsenic in the water sample in mg/L?

SOLUTION	REASONS
$AsO_2^- + \text{RED-K9} \rightarrow AsO_2\text{-RED-K9}^-$	Balanced chemical equation for reaction of arsenite and RED-K9 is given.
1 mol AsO_2^- : 1 mol RED-K9	Mole ratio of reactants is 1:1
$0.050 \text{ M RED-K9} = \frac{0.050 \text{ mol RED-K9}}{1 \text{ L}}$	1 M = 1 mol/L (0.050 mol RED-K9 dissolved in 1 L of solution)
$[44.56 \text{ mL RED-K9}]\left[\frac{1 \text{ L}}{10^3 \text{ mL}}\right] = 4.456 \times 10^{-2}$ L	Convert volume of RED-K9 solution to L since molarity expressed in mol/L.
$\frac{0.050 \text{ mol RED-K9}}{1 \text{ L}}[4.456 \times 10^{-2} \text{ L}] =$ 0.2228×10^{-2} mol $= 2.228 \times 10^{-3}$ mol RED-K9	Compute the number of mol of RED-K9 in 44.56 mL of solution.
2.228×10^{-3} mol of RED-K9 : 2.228×10^{-3} mol of AsO_2^-	Mole ratio of reactants is 1:1
2.228×10^{-3} mol of AsO_2^- : 2.228×10^{-3} mol As	For every arsenite ion, there is 1 arsenic atom so for every mole of arsenite ions, there is 1 mole of arsenic atoms.
$[100.0 \text{ mL}]\left[\frac{1 \text{ L}}{10^3 \text{ mL}}\right] = 1.000 \times 10^{-1}$ L	Convert volume of water sample to L since 1 M = 1 mol/L
$M_{As} = \frac{2.228 \times 10^{-3} \text{ mol As}}{1.000 \times 10^{-1} \text{ L}} = 2.228 \times 10^{-2}$ mol/L	
Mass of 1 mol As = 74.92160 g/mol = 7.492160×10^4 mg/mol	Atomic weight of As from periodic table 1 g = 10^3 mg
$\frac{2.228 \times 10^{-2} \text{ mol As}}{1 \text{ L}}\left[\frac{7.492160 \times 10^4 \text{ mg As}}{1 \text{ mol As}}\right]$ = 1669.253248 mg As/L ≈ 1700 mg As/L	Convert mol/L to mg/L; round to 2 significant figures since the concentration of RED-K9 has 2 significant figures (0.050 M)
Therefore, the concentration of elemental arsenic is about 1700 mg As/L.	

WORKED EXAMPLE

Environmental chemists use the classical Winkler titration (1889) for the determination of dissolved oxygen (O_2) in aqueous solutions such as river water. Through a series of chemical reactions, O_2 in aqueous solutions combines with iodine to form a golden yellow complex. The amount of combined iodine can then be measured by titration (until the golden yellow color disappears) with sodium thiosulfate ($Na_2S_2O_3$). For each mole of dissolved O_2, four moles of sodium $Na_2S_2O_3$ are used in the titration. Trout require a minimum of 8.0 mg/L of dissolved O_2 to survive. You have been given a 100.0 mL sample of local water to analyze for a possible trout-stocking program. After preparing the sample with iodine you need to add 18.50 mL of 0.010 M $Na_2S_2O_3$ solution for the golden yellow color to just disappear. Is there enough dissolved oxygen in this local water to justify a trout-stocking program?

8.0 mg/L dissolved O_2 = 0.0080 g dissolved O_2/L

$$\frac{0.0080 \text{ g } O_2}{1 \text{ L}}\left[\frac{1 \text{ mol } O_2}{31.9988 \text{ g } O_2}\right] = 0.000250009375 \text{ mol } O_2$$

Therefore, 8.0 mg/L ≈ 0.00025 mol/L dissolved O_2 = threshold limit

18.50 mL $Na_2S_2O_3$ solution = 0.0185 L $Na_2S_2O_3$ solution

$$[0.0185 \text{ L } Na_2S_2O_3 \text{ solution}]\left[\frac{0.010 \text{ mol } Na_2S_2O_3}{1 \text{ L}}\right] = 0.000185 \text{ mol } Na_2S_2O_3$$

1 mol O_2 : 4 mol $Na_2S_2O_3$

$$0.000185 \text{ mol } Na_2S_2O_3\left[\frac{1 \text{ mol } O_2}{4 \text{ mol } Na_2S_2O_3}\right] = 0.00004625 \text{ mol } O_2$$

0.00004625 mol O_2 in 100.0 mL sample

$$\frac{0.00004625 \text{ mol } O_2}{100.0 \text{ mL}}\left[\frac{10^3 \text{ mL}}{1 \text{ L}}\right] = 0.0004625 \text{ mol } O_2/\text{L}$$

0.0004625 mol O_2/L

0.0004625 mol O_2/L in water sample> 0.00025 mol O_2/L (threshold value)

Therefore, trout should be stocked since the dissolved oxygen concentration of the local water is greater than the minimum threshold value needed to support trout.

PRACTICE PROBLEMS

Consider the reaction: As + A → As-A
A is blue, As and As-A are colorless. You have 10.0 mL of a solution that contains As with an unknown concentration. You also have a solution of 1.00 M A. You slowly add drops of solution A to the 10.0 mL solution containing A. Explain how you will know when the reaction between A and As is complete.

For the previous problem: If the reaction is complete (the endpoint) after the addition of 20.0 mL of solution A to the arsenic solution, what is the concentration of arsenic in the original unknown solution? What is the concentration of As-A in the final mixture?

Suppose the only method you have available at your lab for determining arsenic content is the colorimetric method seen in the explained problem: $AsO_2^- + \text{Red-K9} \rightarrow AsO_2\text{-Red-K9}^-$.

Unfortunately, your initial 100.0-mL sample may also contains arsenate instead of arsenite that can be quantified with this analytical method. Luckily enough you have L-cysteine available, a compound that can reduce the arsenate to arsenite according to the following reaction: AsO_4^{-3} + 2 L-cysteine → AsO_2^- + 2 L-cystine. After initially titrating with RED-K9 to determine the arsenite concentration (see explained problem), you add excess L-cysteine and re-titrate with RED-K9. An additional 32.7 mL of RED-K9 are required to reach the endpoint.

What is the concentration of arsenic (in milligrams per liter) in this sample (contribution from both the arsenite and arsenate ions?

Figure 2: Titration lesson from the text-only treatment. See text for description.

3.2.2.3 Assignment of volunteers Each volunteer was directed to a website to complete an electronic educational background survey (Appendix C). The survey requested educational data regarding SAT scores and completed math and science courses as well as general background information so that possible relationships of prior knowledge and/or demographics to performance could be analyzed. Volunteers also downloaded, signed, and mailed an informed consent document to the study office (Appendix D). Upon receipt of a completed survey and the informed consent document, a volunteer was randomly assigned to either the technology-rich course or the text-only study guide. Participants assigned to the technology-rich condition were given a password to access the OLI course website. Participants assigned to the text-only condition were given a password to access a different website containing study materials in the form of PDF files.

3.2.3 Duration of the study

The study was conducted between July 25 and August 19, 2005. Communication between participants and the experimenter was entirely by email and/or designated websites. Volunteers were accepted into the study only between July 25 and August 9, 2005, in order to allow sufficient time for them to complete the instructional materials before the end of the study on August 19. During the period between their enrollment and the end of the study, weekly emails were sent to participants encouraging them to complete the materials before the end date. Individual questions from the participants were answered by email within 24 hours. Those questions and responses with general applicability either to the study overall or to a specific treatment group were emailed as well to the other appropriate participants (Appendix E).

3.2.4 Assessment

The purpose of assessment was to determine if the mode of instruction (dynamic, interactive, and context-based format versus text-only format) was related to the learning of stoichiometry as measured by student performance on a test of its concepts and procedures. Two parallel tests that incorporated all of the desired stoichiometric competencies (see section 3.3.2) were constructed. Parallel items were developed by changing cover stories along with the values of given variables. Parallel items may also differ as to which of the related variables the students are asked to determine. The following example illustrates this method of creating parallel items for the online (posttest-1) and campus (posttest-2) exams:

Online exam item: The molecular weight of Compound X is three times the molecular weight of Compound Y. What mass of X will have the same number of molecules as 21 g of Y?

Campus exam item: The atomic weight of element A is twice the atomic weight of element B. What mass of B will have the same number of atoms as 32 grams of A?

The first test (posttest-1) was delivered online at the student's request as soon as the participant had completed the assigned treatment condition (Appendix F). The second test (posttest-2) was administered to all the participants simultaneously during Freshman Orientation Week at CMU (Appendix G). Both posttests were estimated to require 60-90 minutes for completion but students were allotted up to two hours for each test to insure that time was not a limiting factor in their performance. The majority of items were open-ended in that they required students to develop solutions for problems or write explanations to support their responses. When a multiple-choice item was used, at least two of the provided response choices were correct. The following item is an example of a multiple-choice question. The correct responses are underlined.

Laughing gas, N_2O is a weak anesthetic that has been used in dentistry since the late 18th century. The formula, N_2O, means that in a sample of laughing gas (circle all that apply):

(A) <u>For every 100 atoms of oxygen (O), there are 200 atoms of nitrogen (N).</u>

(B) For every atom of nitrogen, there are 2 atoms of oxygen.

(C) For every 2 grams of nitrogen, there is one gram of oxygen.

(D) <u>The compound is 36% oxygen by mass.</u>

(E) <u>The compound is 64% nitrogen by mass.</u>

To receive full credit (5 points) for the item, a student must select all of the correct responses. Partial credit of one point is assigned for each correct response. A complete scoring key for posttest-1 can be found in Appendix I; a complete scoring key for posttest-2 can be found in Appendix J. The exams were designed to test application of procedures and higher reasoning abilities rather than simple recall of facts. A third parallel, albeit shorter, test (posttest-3) was designed for completion in 30-45 minutes (Appendix H). Posttest-3 was administered during a 50-minute class period at the beginning of the second semester introductory chemistry course. It was scored (Appendix K) against criteria similar to those used for scoring posttest-1 and posttest-2.

A table of specifications was constructed relating content to desired learning objectives (see Figure 3). Test items were developed from this blueprint in several ways. Whenever possible, standardized items from the American Chemical Society (ACS) or Advanced Placement (AP) Chemistry exams were used and converted into open-ended response items. For example, the following ACS item tests procedural knowledge about the qualitative analysis of pure substances (see Figure 3).

> A compound of sodium, sulfur, and oxygen contains 29.08% Na, 40.56% S, and 30.36% O. Which formula is correct?
>
> (A) Na_2SO_3, (B) Na_2SO_4, (C) $Na_2S_2O_3$, (D) $Na_2S_2O_8$, (E) $Na_2S_4O_6$

The first sentence of this item was used exactly as written, without the responses provided but with a request for students to show all work. If an item for a desired objective was not available from a standardized source, then a task for that objective was developed jointly by chemistry professor Jordi Cuadros, (Institut Químic de Sarrià, Universitat Ramon Llull) and the author of this dissertation who is a former high school chemistry teacher. For example, no items from either the ACS or AP Chemistry exams test the procedural knowledge needed for determining the molarity of a mixture of solutions (see Figure 3) so the following item was created:

> The contents (A, B, C) of three different bottles of fructose solutions were combined in a 1000-mL volumetric flask. The flask was then filled to capacity with distilled water. Solution A was 74 mL of 0.527 M fructose, solution B was 632 mL of 0.872 M fructose, and solution C was 139 mL of 1.166 M fructose. What was the final concentration of the fructose in the volumetric flask? Please show all your work.

CONTENT OUTLINE		CONCEPTUAL KNOWLEDGE OBJECTIVES		PROCEDURAL KNOWLEDGE OBJECTIVES	
THE MOLE AND OTHER TOOLS OF STOICHIOMETRY		(1) Explain that in chemical reactions atoms and molecules are consumed and produced at the molecular scale (moles) but measured at the macroscopic scale (grams). (2) Identify the mole as a collective numerical quantity that represents Avogadro's number (6.02×10^{23}) of atoms, molecules, etc. (3) Describe the quantity that each subscript in a chemical formula represents. (4) Define the atomic/molecular weight (molar mass) as the number of grams per mole of a substance. (5) Explain the relationship between the number of atoms of an element in a molecule and the number of moles of an element in a mole of a compound. (6) Explain the concentration of a solution in terms of moles, volume, and molarity.		(1) Convert from the macroscopic world (grams) to the molecular world (atoms/molecules) by using atomic/molecular weight (molar mass) and Avogadro's number. (2) Convert from the molecular world (atoms/molecules) to the macroscopic world (grams) by using Avogadro's number and atomic/molecular weight (molar mass). (3) Assemble a sequential combination of dimensional equalities to convert a specified quantity to an equivalent quantity. Use the appropriate number of significant digits when reporting results of calculations involving measured values. (4) Given a periodic table, calculate the molecular weight of a compound. (5) Calculate the number of moles of constituent elements in a given number of moles of a compound. (6) Calculate the masses of the constituent elements in a given mass of a compound. (7) Calculate the percent by mole or by mass if an element in a given compound. (8) Determine the mass or number of moles of solute present in a specified volume of solution of known molarity. (9) Determine the molarity of a solution given the moles or mass of dissolved solute in a specified volume of solvent. (10) Determine the volume of solution with known molarity that is needed to provide a given number of moles or mass of solute. (11) Determine the mass of solute needed to prepare a solution with a specified volume and molarity when given the solute's chemical formula.	
27%	4	50%	2	50%	2
MANIPULATING SOLUTIONS		(1) Compare the effects of dilution on the amount of solute present in, and concentration of, a diluted solution. (2) Describe density as mass per unit volume. (3) Evaluate the sensitivity and specificity of density measurements in chemical analysis.		(1) Describe how to make a specified volume of a diluted solution from a concentrated volume of specified molarity. (2) Calculate the final molarity of each solute after specified molarities and volumes of non-reacting solutions are mixed. (3) Calculate the density of a solution in g/mL having measured (or been given) the mass and volume of a specified solution.	
13%	2	50%	1	50%	1
QUALITATIVE ANALYSIS OF PURE SUBSTANCES		(1) Explain why elemental analysis is necessary but not sufficient to identify a chemical compound. (2) Describe how chemists use elemental analysis,		(1) Compute the empirical formula of an unknown compound from elemental analysis data. (2) Derive the empirical formula of a compound from its molecular formula.	
7%	1			100%	1
REACTION STOICHIOMETRY		(1) Explain that a balanced equation represents the exact mole (molecular) ratios of reactants and products in a chemical reaction. (2) Using a balanced chemical equation, predict the effects of a chemical reaction on the amounts of each substance in a reaction mixture. (3) Explain how titration is used to quantify the amount of solute in a solution.		(1) Given the formulas for reactants and products, write a balanced chemical equation. (2) Calculate the mass of any reactant or product consumed or produced in a chemical reaction when given the mass of one of the other reactants or products. (3) Deduce the percent yield of a specified product of a chemical reaction given the mass of a reactant and the mass obtained of the specific product. (4) Determine the limiting reactant when masses of two or more reactants are given for a chemical reaction. (5) Calculate the mass of product formed from the mass of the limiting reactant. (6) Deduce the mass of any reactant left over after a reaction goes to completion when given the initial masses of the reactants. (7) Deduce the mass fraction of each substance in a binary mixture when given the chemical formulas of the substances, the initial mass of the mixture, and the mass of a common product formed for the complete reaction of the mixture with a common reactant. (8) Given a chemical reaction of the solute and the colors of the reactants and products, design a titration experiment to determine the amount of solute in a solution. (9) Calculate the concentration, mass, or number of moles of solute in an unknown solution from titration data.	
53%	8	38%	3	62%	5

Figure 3: Table of specifications for constructing items for posttest assessments. The content outline includes a summary of the time allocation given to each major topic as well as the corresponding number of questions on each posttest. The objectives include both the number and proportion of conceptual versus procedural items within each content strand.

The online version of the posttest (posttest-1) was available to all the participants from August 11-19, 2005. Participants requested the posttest by sending an email in which they were required to state the estimated time (ranging from a minimum of two hours to a maximum of 22 hours) that they had spent studying the instructional materials. Posttest-1 was emailed to them as a downloadable PDF file (Appendix F). At the same time, their access to the instructional materials website was closed. Participants downloaded, completed, and then faxed or mailed posttest-1 to the study office. They were directed to spend no more than two hours on this exam. A second, proctored, classroom exam (posttest-2) was administered at CMU on August 22, 2005

(Appendix G). Successful performance on a subset of the posttest-2 questions qualified a student for exemption from the mastery examination requirement for Introductory Chemistry[2]. Posttest-1 was used by the researchers to screen for any potential problems but analyses were based upon posttest-2 scores for security reasons, assuming that any potential cheating that might have occurred among students responding remotely would not occur during the on-campus administration of the test. An additional delayed exam (posttest-3) was administered on January 16, 2006, five months after the original study's completion date, to determine retention rates (Appendix H). Twenty of the 45 original participants completed posttest-3.

Scoring criteria for the posttest items were developed jointly by Jordi Cuadros and the author. Each item was allocated five points. In scoring procedural items, researchers deducted one point for a significant figures or arithmetical/units error. Scoring for conceptual items was not standardized but was dependent upon the nature of the question. The author scored all of the items for posttest-1 and posttest-2. Five items each from both posttest-1 and posttest-2 (approximately 15% of the tests) were scored by Jordi Cuadros. Reliability was 100%. Posttest-3 was administered to all of the enrolled students (>100) on the first day of the second semester introductory chemistry course and scored with the same methods used for posttest-1 and posttest-2. A second scorer who is a chemistry graduate also scored a 20-test sample. The few disagreements between that scorer and this author in scoring particular items were resolved through discussion. The scoring key for each posttest can be found in Appendices I-K. Posttest scores were converted to percentages to facilitate comparisons among them. Missing data from Posttest-1 and Posttest-2 were estimated with the expectation maximization algorithms (EM

[2] The professor who taught the introductory chemistry course approved a subset of five questions from the second posttest as equivalent to his mastery examination. Participants who attained a score of 85% or higher on this subset were excused from the in class mastery examination. Analyses in this dissertation are based upon total posttest scores and not this designated subset of questions.

algorithms) from SPSS Missing Value Analysis 14.0 module. Less than three percent of the data used for analysis was generated in this fashion.

3.3 DATA ANALYSIS

Data analysis proceeded in two phases. In Phase 1, exploratory data analysis using box plots or scatter plots was undertaken to get a feel for the data by answering several questions: Is a given factor significant? Does location differ between subgroups? Does variation differ between subgroups? Are there outliers present? In Phase 2, computations of descriptive and inferential statistics were undertaken. Means and standard deviations of posttest scores and SAT scores for different subgroups were calculated as a way of summarizing the data with regard to measures of central tendency and variation. Correlations among posttest scores, treatments, background characteristics, and study practices were inspected to determine possible relationships. Modeling of the data was executed by single regressions of posttest scores on treatment, background characteristics, and study practices to determine the contribution of each variable to learning. Log files from the technology-rich treatment condition were examined to determine the frequency of the OLI participants' interaction with simulations.[3] Each of the following subsections describes how data were analyzed in the service of addressing a specific research question.

[3]We requested that the text-only participants bring their study materials with them when they arrived on campus for the posttest-2 session. Since only four of the 24 participants complied with this request we were unable to analyze the level of engagement for this group.

3.3.1 Influence of instructional materials

Exploratory data analysis of posttest scores from the two treatment groups included the generation of box-and-whisker plots and stem-and-leaf displays to detect patterns and/or gaps in the performances of the text-only and technology-rich treatment groups. Since assignment to treatment group was a randomized process, there was little concern about introducing bias into the results by engaging in data cleansing of outliers (e.g., through trimming, Winsorizing, or deletion) so these refined data were used in subsequent analyses of background, demographics, and study practices. Means and standard deviations were calculated to describe the centrality and variability of the posttest data from the two treatment groups. Regression of the posttest scores on treatment was used to determine the contribution of treatment to the variability in posttest data.

Since both procedural fluency with, and conceptual understanding of, stoichiometric principles are essential for success in the second semester of the introductory chemistry course, posttests were examined for possible performance differences on procedural and conceptual items related to treatment group. In addition to analysis of procedural and conceptual score totals, comparison of the volunteers' performance on selected paired procedural and conceptual items was undertaken to determine if either treatment promoted both fluency and understanding. In a similar fashion, incorrect responses from the paired conceptual and procedural items were compared to determine if either treatment was related to specific error types.

3.3.2 Influence of background experiences and characteristics

Prior knowledge and gender have both been associated with chemistry performance (Boli, Allen, & Payne, 1985; Ozsogomonyan & Loftus, 1979; Shibley, Milakofsky, Bender, & Patterson, 2003; Spencer, 1996). Therefore the composition of the two treatment groups was checked with regard to indicators of the volunteers' prior knowledge (participation in AP or other advanced chemistry coursework and performance on the SAT) and gender. To ascertain whether the backgrounds of the sample of participants were representative of the population from which they came, the participants' SAT scores and gender composition were compared to the entire population of incoming MCS and CIT freshmen. Comparisons of advanced chemistry coursework between study participants and other freshmen in those colleges were not possible since no data were available from the general population.

Individual analyses of the relationship between posttest scores and students' advanced chemistry coursework, SAT performance, and gender were conducted to detect any patterns or gaps related to background. Means and standard deviations were calculated to describe the centrality and variability of the posttest scores as they related to prior chemistry coursework, SAT performance, and gender. Regression of the posttest scores on each background characteristic was used to determine its contribution to the variability in posttest data. Correlations among the background variables were inspected to ascertain the possibility of interactions among the independent variables.

3.3.3 Influence of multiple factors

To develop a model for the influence of multiple factors and/or their interactions on posttest performance, posttest scores were regressed stepwise on treatment, background characteristics, and possible interactions among variables. Prior to this regression analysis, the values for the independent variables were centered (Aiken & West, 1991; DeCoster, 2004) to reduce any possible collinearity between the main effect(s) and the interaction(s).

3.3.4 Influence of learning practices in the technology-rich group

Log files of the volunteers in the technology-rich treatment group were analyzed for insight into possible relationships between learning practices and posttest performance. Estimations of time spent working in the OLI course was provided by the participants. These estimations were compared with log-file times of the course *in use*. Log files of time spent in, and specific interactions with (*clicks*), simulation activities were analyzed with regard to posttest performance. Single regressions of posttest scores on log files of time *in use* and on the number of interactions were conducted to ascertain whether there was a relationship of either factor to performance. Multiple regression of posttest scores on log file data and background characteristics were executed to determine the relationship of any or all factors, or interaction of factors, on posttest performance within the technology-rich group. Factors were centered prior to regression analysis to minimize possible multicollinearity of main effects and any possible interactions.

4.0 RESULTS

The aim of this study was to try to understand the nature of learning of stoichiometry with regard to the design and delivery of its instruction as well as the influence of student background characteristics and study practices. Pre-college student volunteers who were planning to study science or engineering were randomly assigned to either a text-based or technology-rich stoichiometry review course. Their subsequent performance on posttests of stoichiometric concepts and procedures was compared. This research was guided by the following four research questions:[4]

1. To what extent does receiving instruction in a technology-rich learning environment that incorporates a dynamic interface, timely and informative feedback, and an overarching storyline, influence the learning of stoichiometry?
2. How are background experiences and characteristics related to the learning of stoichiometry?
   a. How is the degree of prior knowledge of math and chemistry related to the learning of stoichiometry?
   b. How is the demographic of gender related to the learning of stoichiometry?

---

[4] An additional question guided the research: To what extent does instruction received via a technology-rich learning environment that includes a dynamic interface, timely and informative feedback, and an overarching storyline influence the retention of stoichiometry competencies over a five-month period? Less than half (*n*=20) of the original participants (*n*=45) completed the delayed posttest (posttest-3). The results were inconclusive.

3. To what extent do a technology-rich environment and student background experiences and characteristics work together to influence the learning of stoichiometry?
4. How are learning practices that are facilitated by a technology-rich environment related to the learning of stoichiometry?

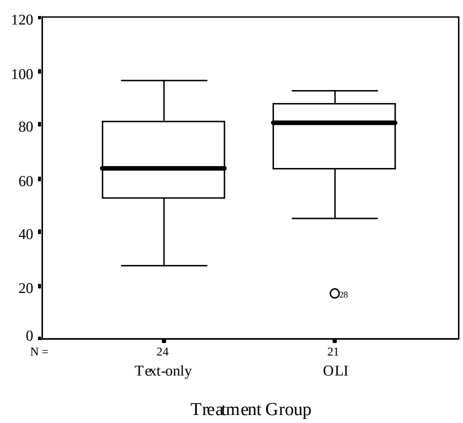
Participant scores from two posttests administered immediately or shortly after the completion of the interventions were analyzed to address the questions posed in this dissertation. To help decide which test or combinations of tests to use we first examined the similarities and differences between them. Students completed posttest-1 individually in unsupervised environments of their own choice after they finished their study materials. All students completed posttest-2, an exam parallel to posttest-1, under proctored conditions no less than five days and no more than ten days later. Serious challenges exist for interpreting the results from both test situations. In the unsupervised tests (posttest-1) students may have cheated; in the supervised test (posttest-2) students may have exhibited substantial test-retest improvement. To investigate these issues, comparisons between the results of the two administrations were made. A comparison of posttest-1 scores (mean=70, *SD*=17) and posttest-2 scores (mean=69, *SD*=21) showed no significant differences and a positive correlation (r=.80, p=.01). These findings suggest that participants did not cheat on posttest-1 by consulting outside help or by using extended time during testing because there is no inflation in the scores from the at-home tests compared to those on campus. The results also indicate no major test-retest gains. Therefore, because of the greater control and consistency of conditions in the administration of posttest-2, the remainder of the analyses of post-treatment performance was conducted with the scores from that posttest.

To answer the first three research questions, exploratory data analyses and regressions were performed on data obtained from posttest-2 scores and background surveys of all the volunteers. To answer the fourth research question, exploratory data analyses and regressions were performed on data obtained from posttest-2 scores, background surveys, and log files of the participants assigned to the technology-rich treatment group.

4.1 EFFECT OF TREATMENT

In order to determine the extent to which stoichiometry learning is influenced by receiving instruction in a technology-rich environment, the distribution of posttest-2 scores in the text-only treatment group (mean=65, *SD*=21) was compared to the distribution of scores in the technology-rich (OLI) treatment group (mean=74, *SD*=21). A single outlier score of *17* in the technology-rich treatment group is nearly three standard deviations below the group mean. When posttest-2 scores are regressed on treatment, only two percent (adj. R^2=.02) of the variability in scores is explained by treatment (β=.21, p=.17). Figure 4 displays box-and-whisker plots of posttest-2 scores by treatment group. The accompanying stem-and-leaf display of scores from the technology-rich treatment group denotes the single outlier score with an asterisk (*).

In order to reduce the sensitivity of the data to the presence of the single outlier score in the technology-rich treatment group, the means of both treatment groups' posttest-2 scores first were trimmed by removing the highest and lowest scores. Then the means were Winsorized by replacing the highest and lowest scores with adjacent scores. Neither adjustment resulted in additional explanation of variability due to treatment. However, when the single outlier score from the technology-rich treatment group is removed from the analysis,[5] treatment explains six percent (adj. R^2=.06) of the variability in performance (p=.05). Table 2 summarizes the analyses with both trimmed and Winsorized means as well as with the deletion of the outlier score.



(A)

```
9|
9|33
8|7778999
8|00114
7|
7|1
6|
6|4
5|
5|
4|5999
4|
3|
3|
2|
2|
1|7*
1|
```

(B)

Figure 4: Box-and-whisker plots showing the distribution of posttest-2 scores by treatment group (A). Stem-and-leaf display (B) of posttest-2 scores from the technology-rich (OLI) treatment group. The outlier score (17*) is nearly three standard deviations below the mean score (mean=74, *SD*=21).

Table 1: Descriptive statistics and regression coefficients for different measures of location for posttest-2 scores from the text-only and technology-rich (OLI) treatment groups. For trimmed means, the single highest and lowest scores were removed from each treatment group. For Winsorized means, the single highest and lowest scores from each treatment group were replaced with adjacent scores. For the *deleted* mean, the outlier score from the technology-rich treatment group was removed; no scores were removed from the text-only treatment group.

Measure	text-only	OLI	adj. R^2	SE	β	p
Sample mean	65	74	.02	21	.21	.17
SD	21	21				
n	24	21				
Trimmed mean	66	76	.06	18	.28	.07
SD	19	16				
n	22	19				

[5]Dr. Kevin Kim, University of Pittsburgh Department of Psychology in Education, personal communication, March 12, 2007.

Winsorized mean	65	75	.04	19	.26	.09
SD	21	17				
n	24	21				
Deleted mean	65	**76**	**.06**	19	.29	**.05**
SD	21	**16**				
n	24	**20**				

4.1.1 Procedural and conceptual scores

Participation in the technology-rich treatment group appears to explain very little of the variation in learning as measured by posttest-2 scores. Therefore a finer-grained analysis of these scores was undertaken to examine possible differences in performance on procedural and conceptual items. The distribution of procedural and conceptual scores for each treatment group was compared (see Figure 5)[6]. The technology-rich group appears to outperform the text-only group on conceptual items (technology-rich: mean=82, *SD*=16; text-only: mean=71, *SD*=20) but the difference between the two treatment conditions is not statistically significant (p=.09). Since both procedural fluency with, and conceptual understanding of, stoichiometric principles is necessary for success in second semester chemistry, a comparison of performance on paired procedural and conceptual items was undertaken to determine if either treatment promoted both fluency and understanding. In particular, the two stoichiometric competencies of major importance to second semester success in solution chemistry are those of dilution and limiting reagents. The ability to manipulate the algebraic expressions of the dilution and limiting reagents procedures, however,

[6]For this and subsequent analyses, the outlier score from the OLI treatment group was deleted. Furthermore, three volunteers from the OLI treatment group and one volunteer from the text-only treatment group did not take posttest-2. These missing overall scores were estimated as described in Chapter 3 but scores for individual items are not available.

has not been shown to insure the conceptual understanding needed for application of these procedures to new venues such as equilibrium and acid-base chemistry (Nakhleh, 1993; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering, 1987; Sawrey, 1990), thus the distinction between procedural and conceptual competence of students in this study may be informative. Results of comparisons between scores on paired items pertaining to this set of skills are reported in the following sections.

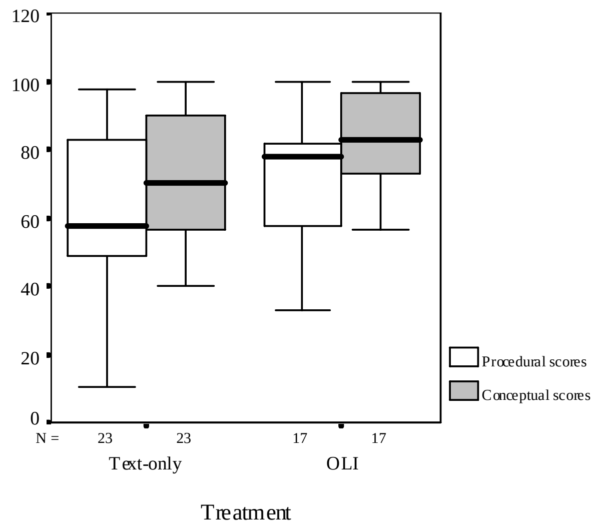


Figure 5: Box-and-whisker plots showing the distribution of procedural and conceptual scores from posttest-2 by treatment group.

4.1.2 Paired conceptual and procedural items: dilution and limiting reagents

The two sets of paired procedural and conceptual items examined were item 12 and item 5 for dilution and item 4 and item 10 for limiting reagents. Each of the procedural items required algebraic manipulations that included conversions between macroscopic-level quantities (grams, liters) and submicroscopic-level quantities (moles). Each of the conceptual items required drawing representations of submicroscopic-level structures (atoms, molecules).

4.1.2.1 Dilution problems Item 12 from posttest-2 is a procedural dilution problem. Students must calculate the concentration of a solution made by mixing three solutions of differing concentrations of the same substance (fructose) and then adding enough water to the mixture to make a final solution of 1 L (1000 mL). The solution to this problem requires the manipulation of the formula for molarity (molarity = $\frac{\text{number of moles}}{\text{1 liter}}$) in order to determine the number of moles of fructose contributed by each of the initial solutions to the final solution. Figure 6 shows item 12 and its solution.

The contents (A, B, and C) of three different bottles of fructose solutions were combined in a 1000-mL volumetric flask. The flask was then filled to capacity with distilled water. Solution A was 74 mL of 0.527 M fructose, solution B was 632 mL of 0.872 M fructose, and solution C was 139 mL of 1.16 M fructose. What was the final concentration of fructose in the volumetric flask?
Solution: Calculate the number of moles (mol) of fructose in each solution and add them together. Then divide the total number of moles of fructose by 1-L to determine the molarity (concentration) of the final solution. Since molarity is moles per liter, volumes given in mL (milliliters) must first be converted to L (liters). $M = \frac{\text{mol}}{\text{L}}$; mol = M x L Moles in solution A = (0.527 M) x (0.074 L) = 0.038998 mol Moles in solution B = (0.872 M) x (0.632 L) = 0.551104 mol Moles in solution C = (1.16 M) x (0.139 L) = 0.16124 mol Total number of moles = 0.751342 mol Total volume = 1-L $M \approx 0.751$

Figure 6: Item 12 from posttest-2, a procedural dilution problem.

Item 5 from posttest-2 is a conceptual dilution problem. The student must draw the actual number of particles (e.g., molecules, atoms) in a given volume of a new solution when two different solutions are combined (see Figure 7). The solution to this problem requires an understanding that the combination process results in the dilution of each of the original solutions so that the final solution contains fewer original particles per unit volume and that the number of these particles is a function of both the original solutions' volumes and the final solution's volume. Therefore, since the contents of the initial 2-L solution become distributed throughout three liters in total, the concentration of small black squares will be reduced from three to two per unit volume (represented by the circle) in the final solution. Since the contents of the initial 1-L solution become distributed throughout three liters in total, the concentration of small clear circles will be reduced from six to two per unit volume in the final solution.

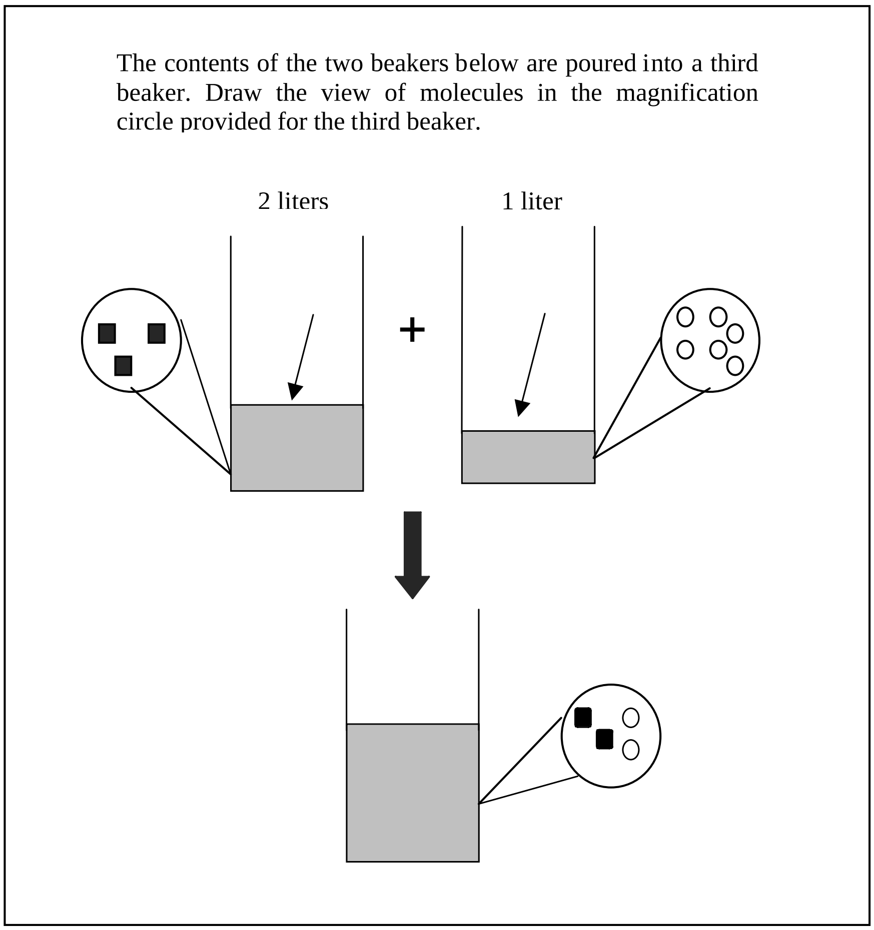


Figure 7: Item 5 from posttest-2, a conceptual dilution problem showing the correct solution.

The number of students in each treatment group that correctly answered both types of dilution problems was tallied. Table 2 displays a comparison of the results. Although a greater percentage of students in the technology-rich (OLI) treatment group than in the text-only group consistently answered the procedural, conceptual, or both type of questions correctly, the differences between the two treatment groups are not significant.

Table 2: Comparison by treatment group of the number of correct responses on procedural (item 12) and conceptual (item 5) dilution questions from posttest-2.

	Correct Responses by Treatment Group	
Dilution Items	Text-Only (*n*=23)	OLI (*n*=17)
Procedural	13(57%)	12(71%)
Conceptual	9(39%)	11(65%)
Both	5(22%)	8(47%)

4.1.2.2 Limiting reagents problems Item 4 from posttest-2 is a procedural limiting reagents problem. Students must determine what remains when given masses of aluminum (Al) and oxygen (O_2) react to form aluminum oxide (Al_2O_3) as the only product. The solution to this problem requires the balancing of the equation for the chemical reaction and the conversion of the masses of the given reactants (reagents) to moles. Errors in either of these sub-procedures will result in an incorrect solution to the problem since both the mole ratios in the equation and the numbers of moles of reactants available are used to calculate which reactant runs out first and therefore how much product can be made. Students must then determine how much of which reactant remains. Figure 8 shows item 4 and its solution.

What masses of what substances remain after 54 grams of aluminum (Al) and 32 grams of oxygen (O_2) react to produce aluminum oxide (Al_2O_3) as the only product?

Solution: First balance the equation for the reaction to satisfy the Law of Conservation of Mass and determine the mole ratio of reacting substances: $4Al + 3O_2 \rightarrow 2Al_2O_3$

Convert mass of each substance to moles since coefficients in balanced equation represent moles:

$54 \text{ g Al} \left[\frac{1 \text{ mol Al}}{27 \text{ g Al}}\right] = 2 \text{ mol Al}$; $32 \text{ g } O_2 \left[\frac{1 \text{ mole } O_2}{32 \text{ g } O_2}\right] = 1 \text{ mol } O_2$

The mole ratio of Al:O_2 in the balanced equation is 4:3; have reactants in a 2:1 ratio

O_2 is the limiting reactant since it will run out before Al: 1 mol O_2 will react with 4/3 mol Al.

Leftover Al will be (2-4/3) mol or 2/3 mol.

Convert to grams: $2/3 \text{ mol Al} \left[\frac{27 \text{ g Al}}{1 \text{ mol Al}}\right] = 18 \text{ g Al}$

Determine amount of Al_2O_3 made:

The mole ratio of O_2: Al_2O_3 in the balanced equation is 3:2.

Have 1 mol O_2 so can make 2/3 mol Al_2O_3: $2/3 \text{ mol } Al_2O_3 \left[\frac{102 \text{ g } Al_2O_3}{1 \text{ mol } Al_2O_3}\right] = 68 \text{ g } Al_2O_3$

Therefore, what remains: 18 g Al and 68 g Al_2O_3; the O_2 is all used.

Figure 8: Item 4 from posttest-2, a procedural limiting reagents problem.

Item 10(A) from posttest-2 is a conceptual limiting reagents problem. The students are asked to draw the number of various molecules of substances remaining after a reaction takes place. The solution to this problem requires that the students understand that all the substances in the initial condition are accounted for in the final condition (Law of Conservation of Mass) and that no extra materials are added. Un-reacted materials as well as products must be displayed since the question requests that substances *remaining* after the reaction be shown. Figure 9 shows item 10(A) with the correct response. All of the chlorine is consumed and is therefore considered to be the limiting reagent since it *limits* how much product (ICl_3) can be synthesized.

Chlorine (Cl_2) and iodine (I_2) react to give ICl_3. (**X**) is a mixture of chlorine and iodine. Draw the resultant substances in (**Y**) after the reaction goes to completion.

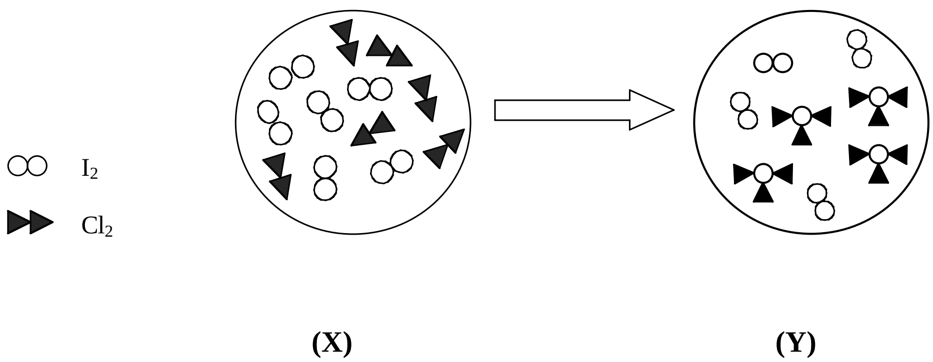


Figure 9: Item 10 from posttest-2, a conceptual limiting reagents problem showing the correct solution.

The number of students in each treatment group that correctly answered both types of limiting reagents problems was tallied. Table 3 displays a comparison of the results. Although a greater percentage of students in the technology-rich (OLI) treatment group than in the text-only group correctly answered the procedural or both types of questions, the differences between the two treatment groups are not significant. However, the percentage of OLI participants with the correct response to the conceptual limiting reagents problem is significantly greater than the percentage of text-only participants with the correct response (Pearson's Chi Square, p = .05).

Table 3: Comparison by treatment group of the number of correct responses to procedural (item 4) and conceptual (item 10A) limiting reagents questions from posttest-2.

	Correct Responses by Treatment Group	
Limiting Reagents Items	Text-only (*n*=23)	OLI (*n*=17)
Procedural	7(30%)	7(41%)
Conceptual	12(52%)	14(82%)*
Both	5(22%)	7(41%)

*Pearson's Chi Square, *p*=.05.

4.1.3 Procedural and conceptual errors

Although the trend is for participants in the technology-rich treatment group to outperform those in the text-only group, the variability of performance within the two treatment groups on procedural and conceptual items precludes any definitive conclusions (other than with the conceptual limiting reagents item). Therefore an examination of the errors was undertaken to determine whether one treatment tended to produce more of a significant misunderstanding than did the other treatment.

4.1.3.1 Errors with dilution problems Fourteen of the 40 participants exhibited errors when responding to the procedural dilution question in which three different fructose solutions are combined (see Figure 6). The most frequent error was applying the incorrect volume in determining the molarity (concentration) of the final solution. Eleven (79%) of the participants in error summed the volumes of the combining solutions (845 mL or 0.845 L) to determine the final volume rather than using the final volume provided in the question (1 L). At first glance this type of error appears to be shallow in nature since the participants do apply the correct overall procedure and realize that molarity depends upon both the number of moles and the volume of solution in which they are contained. Perhaps the error was due to not carefully reading the problem statement. In order to support this explanation of error, these participants' responses to the paired conceptual dilution item (see Figure 7) were examined. Four of the paired conceptual responses (out of the 11 possible) were correct. This proportion of correct responses is significantly different (p=.01) from 11 possible correct conceptual responses. Therefore, the procedural error (for total volume) may be indicative overall of inert knowledge of dilution from rote execution of a procedure without a conceptual understanding of the process itself. Furthermore, the text-only group exhibited six of the procedural errors (out of 11) for which only one participant correctly responded to the paired conceptual item (17%) whereas the technology-rich group exhibited five of the procedural errors for which three participants correctly responded to the paired conceptual item (60%). Although the trend favors the technology-rich group for shallowness (versus depth or severity) of the procedural error, the differences in proportions of procedural error accompanied by conceptual understanding between the two treatments are not significant. The remaining three errors (out of 14 total) exhibited with the procedural dilution problem involved the use of an incorrect procedure for determining molarity. These three errors all originated within the text-only group. Two of these participants did answer the paired conceptual problem correctly suggesting that although the concept of dilution is understood, this knowledge is not translated to procedural implementation. Table 4 summarizes the error analysis by treatment group of the procedural dilution item from posttest-2.

Table 4: Type and frequencies of errors with procedural dilution problem by treatment group. Numbers in parentheses are the correct number of responses to the paired conceptual item.

	Treatment Group	
Error Types	Text-only (*n*=23)	OLI (*n*=17)
Volume	6(1)	5(3)
Formula	3(2)	0
Total	9(3)	5(3)

A greater percentage of participants exhibited errors with the conceptual dilution item (50%) than with the procedural dilution problem (38%) but the difference is not significant overall or between the text-only and technology-rich treatment groups. These conceptual errors are distributed nearly equally between two types: (1) the dilution process is evident but the resulting concentration is incorrect, or (2) the dilution process is absent and an additive process is used. A third type of error that occurred twice within the text-only group indicates a reaction among the shapes resulting in a new product since the diagram of the final solution contains triangles instead of the original circles or squares. However, since there is no accompanying explanation of the reaction process by any participant, it is impossible to determine if the final concentration of triangles shown is the result of dilution or addition. Figure 10 displays a correct response as well as the three types of errors from the conceptual dilution problem. Only one participant (from the text-only group) exhibited an error with both the procedural and conceptual dilution problems. The conceptual error was additive in nature and the procedural error involved an incorrect procedure for determining molarity.

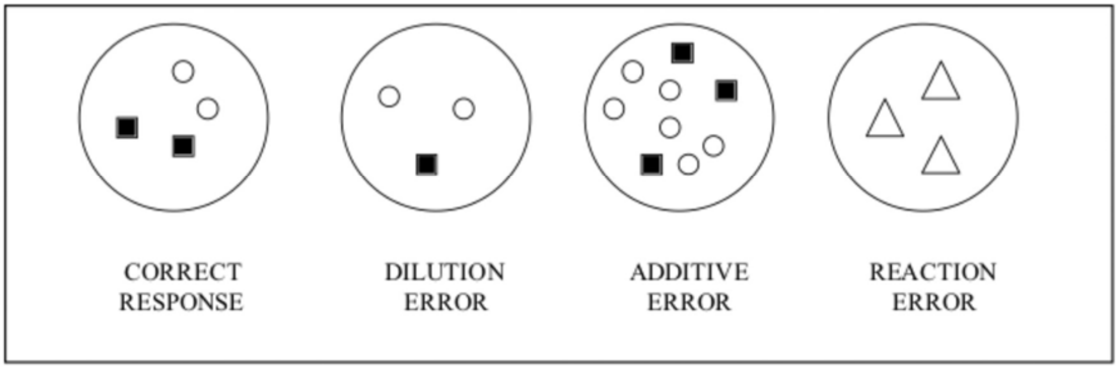


Figure 10: Correct response and examples of the major error types exhibited by participants for the conceptual dilution item.

4.1.3.2 Errors with limiting reagents problems Twenty-one of the 40 participants exhibited errors when responding to the procedural limiting reagents question in which aluminum and oxygen combine to produce aluminum oxide (see Figure 8). Half of the incorrect responses (10) made no mention of the mass of aluminum oxide formed although this product certainly would be among the substances remaining after the reaction stops, due to the limiting reagent being used up. The same number of participants from each treatment group exhibited this error. At first glance one could conclude that this error results from an oversight on the part of the participant or even an interpretation of the term *remains* in the question to mean what is leftover from the original reaction mixture (aluminum and oxygen) and not what is newly produced. Therefore a comparison was made between these responses and those responses to the paired limiting reagents conceptual question (see Figure 9). Six (out of 10) of the responses to the conceptual question were correct, and again the same number of participants from each treatment group answered correctly.

A second type of error exhibited with the procedural problem's solution involved correctly balancing the equation for the reaction but failing to execute the procedure correctly due to the use of incorrect molar masses (even though molar masses were provided in an information sheet attached to the posttest) or to interpret the results of a mathematical operation (i.e., identifying what is used up as what is left over or vice versa). Seven participants from the text-only group and two participants from the OLI group produced this type of error. Since an execution error may reflect a weak conceptualization of limiting reagents, a comparison of these execution error responses to the performance on the conceptual limiting reagents problem was made. Two (out of seven) of the participants from the text-only group provided correct responses to the conceptual limiting reagents problem whereas one of the two participants from the technology-rich group did. These results suggest that errors with limiting reagents procedures are related to a weak conceptual understanding of the topic, especially by the text-only group. A multistep calculation may be difficult to execute from memory without the ability to reason about the purpose of each step. Any differences between the two treatment groups are inconclusive.

The third and final error type exhibited by one participant from each treatment group involved the incorrect balancing of the reaction equation but the correct execution of the mathematical calculations, albeit resulting in an incorrect solution. Both of these participants correctly answered the conceptual limiting reactants problem suggesting that the error in the equation balancing may have been a careless mistake. Table 5 summarizes the error analysis by treatment group of the procedural limiting reagents item from posttest-2. There are no significant differences in the total number or types of errors between treatment groups. Furthermore, there are no significant differences in the proportion of procedural errors accompanied by correct conceptual responses between treatment groups.

Table 5: Type and frequency of errors with the procedural limiting reagents problem by treatment group. Numbers in parentheses indicate the number of correct responses to the paired conceptual item.

	Treatment Group	
Error Types	Text-only (*n*=23)	OLI (*n*=17)
No product "remains"	5(3)	5(3)
Execution errors	7(2)	2(1)
Unbalanced equation	1(1)	1(1)
Total	13(6)	8(5)

Fewer participants (14 vs. 21) overall exhibited errors with the conceptual limiting reagents problem (see Figure 9) than with its paired procedural problem (see Figure 8). However, only three of these participants were from the technology-rich group. This difference in proportion of error per treatment group is significant (p =.05) and favors the technology-rich treatment. One third of these conceptual errors (5 total: 2 in technology-rich group, 3 in text-only group) exhibited the correct amount of product but no excess reagent. The remaining errors (9) were different for each individual and ranged from no response to varying amounts of reagents or product specified by the problem to even representations of substances not specified by the problem. Figure 11 displays the correct response as well as examples of error types for the conceptual limiting reagents problem. Although the concept of limiting reagents and the procedural execution of this type of problem have not been mastered by a large segment of the study's participants, the data support an advantage for the technology-rich group.

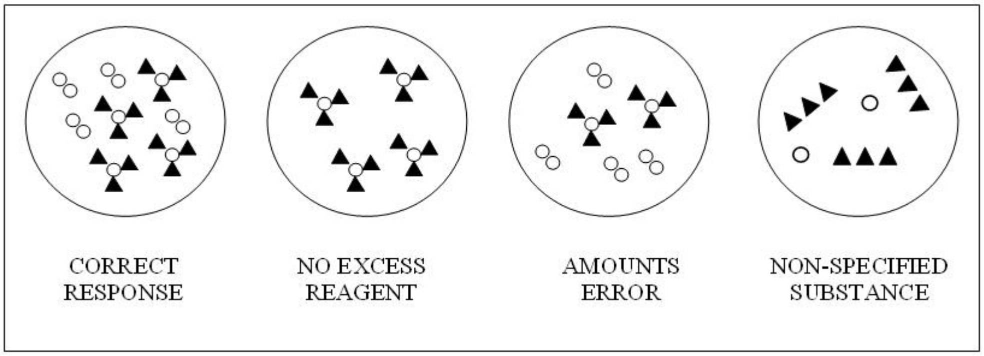


Figure 11: Correct solution and examples of the major error types exhibited by participants in response to the conceptual limiting reagents item.

4.1.4 Summary of findings for the effect of treatment

Performance by the OLI treatment group exceeded that of text-only group. However, treatment condition explained little of the variability (6%) in posttest-2 scores. Therefore a closer examination was made of overall performance on procedural and conceptual items. Although the OLI group consistently outperformed the text-only group, the differences in performance on procedural and conceptual items, both within and between groups, were not significant. Close examination of paired procedural and conceptual items for dilution and limiting reagents showed a similar pattern of favoring OLI treatment. Participants in the OLI group proportionally made both fewer procedural and fewer conceptual errors than did the participants in the text-only group.

4.2 EFFECT OF BACKGROUND EXPERIENCES AND CHARACTERISTICS

The findings to this point suggest only a small advantage for the carefully designed technology-rich chemistry course. Certain background experiences and characteristics may be more closely related to stoichiometry posttest performance than participation in a brief review course. In order to address the question of the relationship between participant background experiences and characteristics and the learning of stoichiometry, the distribution of posttest-2 scores with regard to prior knowledge and gender was explored. Sources of data for prior knowledge included advanced high school chemistry coursework and SAT scores. AP chemistry is a second course offered at the high school level; it is modeled after a general introductory college chemistry course. Participants who have completed the AP chemistry course or a similar advanced course in high school would have had more experience with stoichiometry than those who had only completed the general high school course. Therefore posttest-2 scores were analyzed with regard to AP course completion across treatment groups. Science performance in general, and chemistry performance in particular, is strongly influenced by mathematical and general verbal competence; an estimate of that competence is available from scores on the math and verbal SAT. Therefore posttest-2 scores were analyzed with regard to SAT scores across treatment groups. Gender differences in learning science content have been documented and are of concern because they imply future inequities. Therefore posttest-2 scores were analyzed with regard to gender across treatment groups.

As a check of the randomization process in creating equivalent groups with regard to background attributes, each treatment group was examined with respect to AP completion, SAT scores, and gender composition. Although there were small variations in SAT scores and in the percentage of males, with both favoring the technology-rich (OLI) treatment group, there were no significant differences between treatment groups with regard to the proportion of participants completing AP (or a comparable second chemistry course), the mean SAT score, or the proportion of males. Table 6 summarizes the background composition of the two treatment groups.

Table 6: Background attributes of treatment groups.

	Treatment Group	
Background attributes	Text-only (*n*=24)	OLI (*n*=21)
AP completion	16 (67%)	9 (43%)
SAT scores (mean ± *SD*)	1369 ± 101	1389 ± 104
Number (proportion) of males	13 (54%)	14 (67%)

4.2.1 Background experience: AP Chemistry

Students who complete a second chemistry course in high school, such as AP, are afforded the opportunity to apply and practice stoichiometry concepts and procedures in advanced topics such as equilibrium and acid-base chemistry, whereas most first-year high school chemistry courses only present the stoichiometric procedures divorced from their use in the domain. It is reasonable to expect that those participants with AP experience will outperform those with no AP experience on the posttest. Therefore a comparison of posttest-2 scores between those participants with (mean=74, *SD*=17) and without AP (mean=67, *SD*=22) experience across treatment groups was made.[7] Exploratory analysis suggests that participation in an AP

[7]This and all subsequent analyses were completed after deleting the outlier score detected during the exploratory analysis for the effect of treatment (see section 4.1).

chemistry course in high school is not related to performance on the study's posttest. When posttest-2 scores are regressed on AP, less than one percent of the variability in scores is explained by the completion of an AP course and the standardized coefficient (β=.18) is not significant (p=.25). Previous analyses of the effect of AP on college performance have found that while student performance on AP examinations (grade of 3 or higher) is strongly related to college performance, merely participating in AP or other honors-level courses in high school is not a valid predictor of superior performance in college (Geiser & Santelices, 2004). Therefore the lack of a relationship between taking AP chemistry and performance on the posttest is not surprising.

4.2.2 Background experience: SAT

Since chemistry performance has been linked to mathematical and verbal competence, participants' SAT scores were used as indicators of prior knowledge in these areas. These scores ranged from 1160 to 1590 (mean=1382; *SD*=100). Posttest-2 scores ranged from 28[8] to 97 (mean=70; *SD*=20). Figure 12 shows box-and-whisker plots of the posttest-2 scores and SAT scores. Although the distribution of SAT scores is symmetrical, the distribution of posttest-2 scores is slightly negatively skewed.

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[8] Recall that the outlier score of 17 detected in the treatment analysis has been deleted from further analysis (see section 4.1).

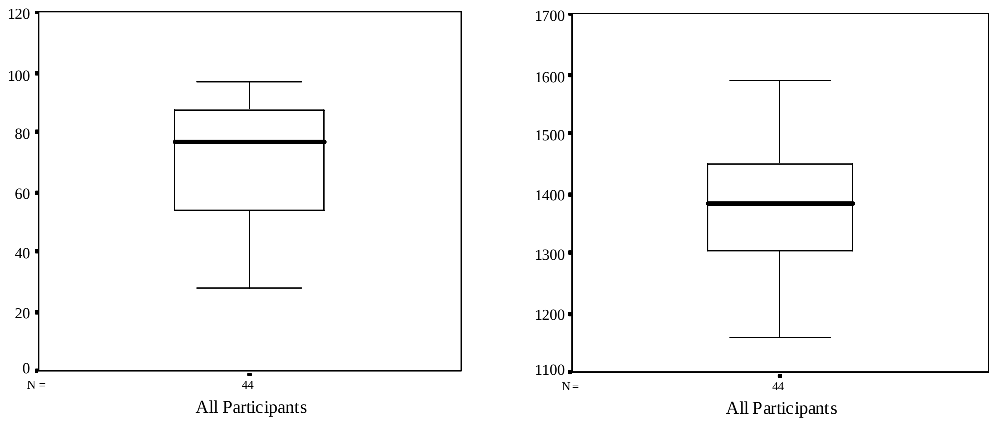


Figure 12: Box-and-whisker plots showing the distribution of participants' posttest-2 scores (left) and SAT scores (right).

A scatter plot of posttest-2 and SAT scores does indicate a significant positive correlation (r=.56, p=.001) between the two variables (see Figure 13). When posttest-2 scores are regressed on SAT scores, β=.51 (p=.001) and 25% of the variability (adj. R^2) in the posttest-2 scores is explained by the SAT scores. These results support the previous findings of a positive relationship between SAT scores and chemistry performance (Ozsogomonyan & Loftus, 1979; Spencer, 1996).

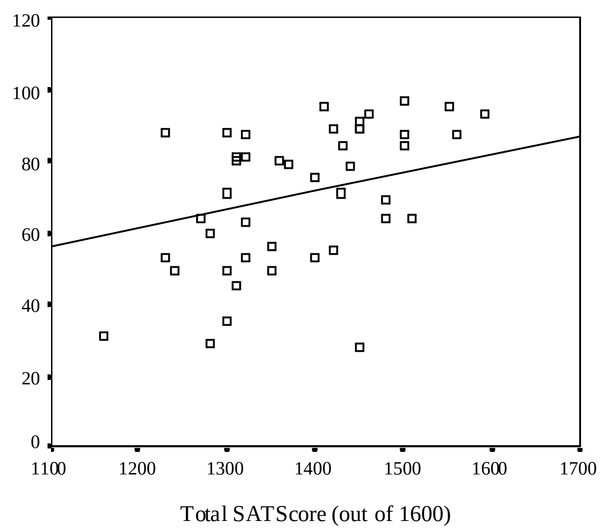
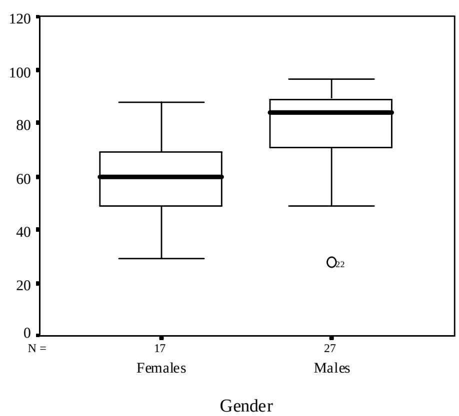


Figure 13: Scatter plot of SAT scores and posttest-2 scores including regression line: Posttest-2 score = 0.10 (total SAT) – 70.17

4.2.3 Demographics: gender

Since documented gender inequities in science performance are a concern (Grigg, Lauko, & Brockway, 2006), a comparison was made between male and female posttest-2 scores across treatment groups. Figure 14(A) displays box-and-whisker plots of posttest-2 scores by gender. This exploratory data analysis suggests that posttest-2 performance is related to gender, with males having the advantage (r=.49, p=.001), even with the presence of a male outlier score (28) nearly three standard deviations below the male mean score (mean=78; SD=17) (see Figure 14[B]). When posttest-2 scores are regressed on gender, 22% of the variability in scores (adj. R^2) is explained by gender with β=.49 (p=.001).



9	557
9	133
8	7778999
8	0144
7	58
7	11
6	
6	3
5	56
5	3
4	9
4	
3	
3	
2	8*
2	
1	
1	

(A) (B)

Figure 14: (A) Box-and-whisker plots showing the distribution of posttest-2 scores by gender. Males (mean=78, SD=17) significantly outperform females (mean=58, SD=18). (B) Stem-and-leaf display of male posttest-2 scores. The outlier score (28*) is nearly three standard deviations below the mean male score.

4.2.4 SAT scores and gender

The trend in performance results by gender is similar to that by SAT scores: males and higher SAT scores are associated with higher posttest-2 scores whereas females and lower SAT scores are associated with lower posttest-2 scores. Figure 15 displays box-and-whisker plots of SAT scores by gender. This exploratory data analysis suggests that SAT performance is related to gender (*r*=.47, *p*=.001), with males (mean=1419; *SD*=84) significantly (*p*=.001) outperforming females (mean=1324; *SD*=98). When SAT scores are regressed on gender, 20% of the variability (adj. R^2) in scores is explained by gender, with β=.47 (*p*=.001).

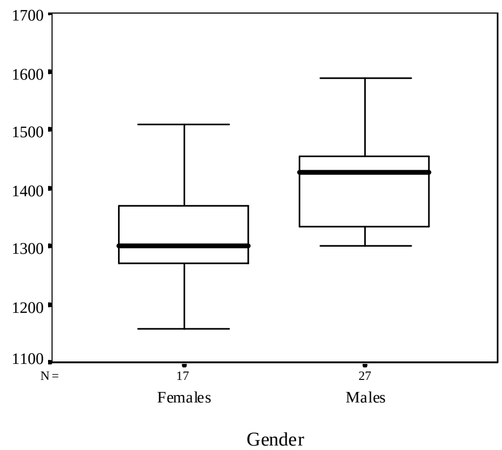


Figure 15: Box-and-whisker plots displaying the distribution of SAT scores by gender.

4.2.5 Summary of findings for the effect of background

Prior knowledge and gender have been documented as predictors of performance in chemistry. Although participation in a second (advanced) high school chemistry course was not related to posttest-2 performance, both SAT scores and gender were correlated with performance and individually explained about a quarter of the variability in the posttest-2 scores.

The similarity of the relationship of SAT performance and gender individually with posttest-2 scores invited a subsequent investigation of the relationship between SAT scores and gender.

4.3 EFFECT OF COMBINED FACTORS

Within the context of this study, the learning of stoichiometry appears to be related significantly to participants' background characteristics and to be little affected by treatment condition. Individually, both SAT scores (25%) and gender (22%) explain more of the variability in posttest-2 scores than does treatment condition (6%). Therefore each of these variables was systematically added (stepwise) to the regression equation to determine a model that best explains the participants' posttest-2 performance (see Table 7). SAT and gender together explain nearly one third of the variability in performance on posttest-2, with high scorers on the SAT and males having the advantage.

To determine if any interactions between or among variables (such as gender and SAT) were related to posttest-2 performance, each variable (treatment, SAT, gender) and all possible interaction variables (gender-SAT, gender-treatment, SAT-treatment, gender-SAT-treatment) were systematically added (stepwise) to the regression equation. The same two models resulted, with no explanation of variability due to any interaction variable or to treatment.

Table 7: Stepwise multiple regression analysis using treatment, SAT score, and gender to explain performance on posttest-2.

Model	adj. R^2	*SE*	β	*p*
SAT	.25	17.1	.51	.001
SAT + Gender	.31	16.4	.36, .32	.02, .03

4.4 THE CMU EFFECT

To ascertain whether male SAT scores differ from female SAT scores in the general population from which the sample under study originated, a comparison of SAT scores by gender from the Mellon College of Science (MCS) and the Carnegie Institute of Technology (CIT) was made. Table 8 is a summary of the findings. In each group, males outperform females on both the verbal and math sections of the SAT. The differences (.54 *SD*) between genders are significant for the overall population on the math section (p=.0001). Since freshman success as well as science performance has been linked to SAT performance, females in MCS and CIT may be at a distinct disadvantage during the introductory chemistry course. This difference in performance between genders is even more pronounced within the sample of students from MCS and CIT who participated in the study: a 0.66 standard deviation difference in SAT verbal scores and a 1.3 standard deviation difference in SAT math scores. Furthermore, there are no significant differences in verbal or math scores between male participants and male non-participants but there *are* significant (p=.01) differences in math scores between female participants and female non-participants. Female participants' math scores are significantly lower (.69 *SD*), a finding that may suggest an underlying difference in motivation between the males and females who agreed to participate in the study. Female participants may have chosen to *prep* themselves prior to beginning their studies of college science courses.

Table 8: Comparison of mean SAT scores from MCS and CIT freshmen.

	SAT Section	
Group	Verbal Mean(*SD*)	Math Mean(*SD*)
Participants		

Females (*n*=18)	636(77)	682(43)
Males (*n*=27)	683(65)	735(39)
Non-participants		
Females (*n*=182)	653(76)	715(53)
Males (*n*=401)	660(72)	740(48)
Overall		
Females (*n*=200)	651(76)	712(53)
Males (*n*=427)	662(72)	739(47)

4.5 LEARNING PRACTICES IN THE TECHNOLOGY-RICH ENVIRONMENT

Participants in the technology-rich group self-reported spending significantly (p=.01) more minutes working (mean=625; *SD*=297) with their study materials than the participants in the text-only treatment group (mean=381; *SD*=295). Log files generated by the actions of the technology-rich participants both supported their self-report times and also enabled a closer examination of specific study practices of the OLI participants.

4.5.1 Time engaged with study materials

To explore whether time engaged with the study materials was related to performance on posttest-2 within the technology-rich treatment group, a scatter plot of the data was generated (see Figure 16). There is no significant correlation between time engaged with the materials and posttest-2 performance (r=-.01, p=.98). Although log files accurately report when the OLI program is *on*, students may not be engaged during that entire period. They may step away from the computer to answer the phone or grab a snack. In addition, study time itself may not be an optimal indicator of learning since some learners require more time on task than others to achieve the same level of understanding (Bloom, 1974; Carroll, 1963; Cooley & Leinhardt, 1980; Gettinger, 1984). A better gauge may be one that measures what the learner is doing during the time engaged with the study materials. Even though the chemistry content of the text-only and technology-rich treatments was designed to be comparable, the instructional delivery of the OLI course also included multiple opportunities for interactive problem solving and exploration with feedback. Therefore an analysis of whether the level of engagement with these interactive opportunities that provide feedback was related to posttest performance within the OLI treatment group was undertaken.

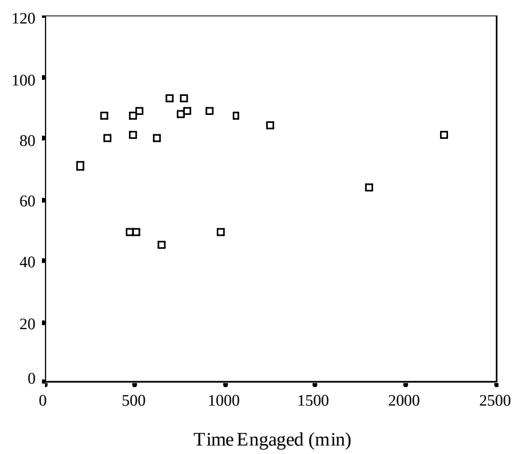


Figure 16: Scatter plot of time engaged with OLI study materials and posttest-2 scores.

4.5.2 Interaction with the Virtual Lab

The technology-rich OLI course features the Virtual Lab, an interactive interface that provides students with both support and feedback when solving stoichiometry problems. Support is provided through visualizations of submicroscopic and macroscopic interactions of chemical entities, which can aid in the connection and integration of the multiple levels of chemical knowledge. In addition, problems based in the Virtual Lab provide hints that may be requested by the users as well as feedback to their proposed solutions. Yet measuring time spent in Virtual Lab activities is subject to the same questions of engagement as arose from the measure of time spent overall in the course. An exploration of the participants' actual number of interactions with the Virtual Lab may be a more accurate measure of engagement with the study materials. Each time a participant's mouse clicks in the Virtual Lab interface it is recorded as an *event* in the user's log file. A scatter plot showing the distribution of the posttest-2 scores and the total number of Virtual Lab events for each participant reveals a positive correlation (r=.43, p=.06); but the wide range (0-5000) of the number of Virtual Lab events across participants suggests a scale issue (see Figure 17).

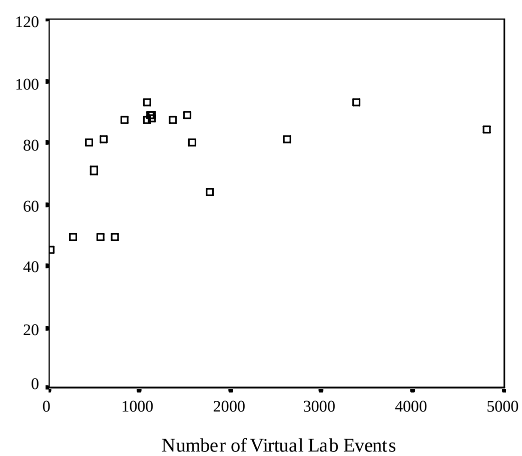


Figure 17: Scatter plot of the relationship between Virtual Lab events and posttest-2 scores by the OLI group.

To address the scale issue, a scatter plot was constructed of the posttest-2 scores and the $\log_{10}$ of the numbers of Virtual Lab events. As shown in Figure 18 there is a strong and statistically significant correlation (r=.65, p=.02) between these two variables. When posttest-2 scores are regressed on the $\log_{10}$ of the numbers of Virtual Lab events, 39% of the variability in scores (β=.65, p=.002) is explained by the level of participant interaction with Virtual Lab learning activities. These results suggest that the degree to which students take advantage of the instructional interaction afforded by the technology-rich treatment, not just being assigned to the treatment, is highly related to learning as measured by posttest-2 scores.

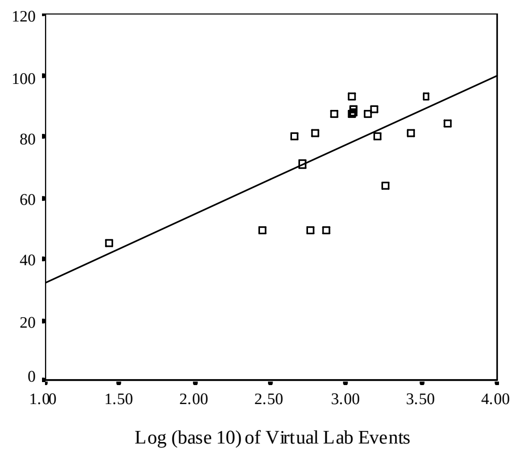


Figure 18: Scatter plot of logarithms (base 10) of numbers of Virtual Lab events and posttest-2 scores including the regression line: posttest-2 score = 9.98 + 22.55 ($\log_{10}$ number of Virtual Lab events).

Stepwise regression of posttest-2 scores on the $\log_{10}$ of the numbers of Virtual Lab events, gender, and SAT scores yields two explanatory models for performance in the technology-rich treatment group. Both models attribute a high proportion of the variability in performance to the level of engagement with the Virtual Lab. These models suggest that engagement with an interactive resource may overcome deficiencies in prior knowledge and gender inequities (see Table 9). To determine if any interactions between or among variables (such as gender and Virtual Lab interactivity) were related to posttest-2 performance, each variable (gender, Virtual Lab interactivity, SAT) and all possible interaction variables (gender-SAT, gender-Virtual Lab interactivity SAT-Virtual Lab interactivity, gender-SAT-Virtual Lab interactivity) were systematically added (stepwise) to the regression equation. The same two models resulted with no explanation of variability due to any interaction variable. Care should be taken in drawing conclusions from the second model (Log_{10} Virtual Lab events + gender), however. The small size (n=20) of the technology-rich treatment group together with its low number of female participants (six out of 20) calls into question the conclusiveness of this particular model.

Table 9: Regression models for posttest-2 performance in the OLI treatment group. Log_{10} of the number of Virtual Lab events, gender, and SAT scores were added stepwise to the regression equation.

Model	*Adj. R^2*	β	*SE*	p
Log_{10} Virtual Lab events	.39	.65	12.8	.002
Log_{10} Virtual Lab events + gender	.58	.49, .47	10.6	.01, .01

4.6 SUMMARY OF FINDINGS

A review of the performance of the participants on posttest-2 indicates that prior knowledge and gender are stronger predictors of success than assignment to either treatment group. Gender and SAT score are highly correlated for the participants for this study, but there is no interaction between these two variables that explains any of the variability in performance. The correlation of SAT score and gender forced a closer look at the volunteer pool and the population from which it was drawn. This examination revealed a differential in the SAT scores of females and males who had matriculated in MCS and CIT. Although the mean SAT score for the male volunteers was no different from the overall male population, the mean SAT score for the female volunteers was significantly lower than that for the overall female population. These observations suggest that females with lower SAT scores may have self-selected for the study as a means of *prepping* themselves for future coursework in which they perceived they might struggle.

When the performance of those participants in the technology-rich group is examined, the level of interactivity with the Virtual Lab appears to compensate for deficiencies in prior knowledge as measured by the SAT but not for gender. Although there is no statistically significant correlation ($r=.33$, $p=.16$) of Virtual Lab interactivity with gender (which may be due to only six out of the 20 OLI participants being female), a system that encourages interactivity with the Virtual Lab when working with the study materials from the OLI course may promote performance with stoichiometric competencies.

5.0 DISCUSSION

This study was motivated by the desire to provide incoming freshman college students with a learning experience that would result in their fluid and flexible use of the stoichiometric competencies needed for the complex demands of solution chemistry problem solving. Although stoichiometry is addressed in most high school courses, college instructors have noticed that students do not have command of this central tool for chemistry work even if the content is reviewed early during a freshman chemistry course by direct instruction or self-study (D. Yaron, personal communication, May 19, 2004.). Volunteers were assigned randomly to one of two cognitively informed sets of stoichiometry instructional materials. A comparison of student performance on a posttest of stoichiometry topics was made in order to determine if dynamic expositions, immediate supportive feedback, and an overarching cover story all facilitated through online technologies promoted greater learning outcomes than studying only from text-based resources. In addition to treatment condition, posttest performance was analyzed with regard to the participants' background characteristics and demographics, study practices, and interactions among any of these variables.

5.1 TREATMENT CONDITION

There were two major findings from comparing posttest performance between the technology-rich and the text-only treatment group. First, even after multiple instructional opportunities, students overall did not have a firm grasp of stoichiometry concepts or procedures. The mean posttest score overall was 69%, a failing mark on most grading scales.[9] Second, although the performance of the technology rich group (mean=76, *SD*=16) statistically exceeded that of the text-only group (mean=65, *SD*=21), the difference was small and the variability in both groups was high. Closer examination of performance on specific conceptual items did reveal a significant difference between the two treatments for supporting a conceptual understanding of limiting reagents and a strong tendency to support dilution comprehension that favored the technology-rich group. Since both the flexible use of stoichiometric concepts and fluid use of stoichiometric procedures are foundational to solution chemistry (acid-base, equilibrium) problem solving, the online learning experiences could be enhanced by providing more examples and tasks for each topic, and/or by revising the example and task format to encourage greater engagement of the participants.

[9] Six participants scored high enough on the subset of problems identified for the mastery requirement described earlier (See Section 3.2.4) There were no significant differences in the proportion of participants from either treatment group or in the proportion of males or females that achieved mastery status.

5.1.1 Increasing the number of examples and tasks

When compared to four other online chemistry courses, the OLI course used as the technology-rich treatment in this study provided the highest degree of cognitive complexity[10] among, but the fewest number of, examples and tasks for each stoichiometric topic (Appendix A). Perhaps the developers felt that, since this course served as a review, the content was already familiar to the users and therefore the need for numerous examples and tasks was not as important as it would have been if the content were new. Even so, the OLI course only provided an average of two examples and less than five tasks per topic. Considering that the quantity and variety of examples are important for students to be able to compare and to distinguish relevant from incidental features for specific problem types, the explication of only two examples may not have been sufficient for meaningful learning. Likewise, the practice opportunities provided by less than five tasks per topic may not be sufficient for development of any degree of fluidity or accuracy with stoichiometric procedures.

5.1.2 Revising the structure of examples and tasks

The relationship between conceptual understanding of, and procedural fluency with, stoichiometry competencies is not a simple one due at least in part to the tripartite nature of chemistry knowledge. The limiting reagents and dilution conceptual items from the study's posttest required that a participant work with only one (submicroscopic) of the three levels of

[10]Tasks that support incorporation of new knowledge into, reorganization of, and strengthening of connections within, the learner's cognitive structure are deemed to be cognitively complex. These tasks may require the integration of two or more procedures, reasoning without algorithmic procedures, or be situated within the context of the laboratory or real life for which there is no defined solution path. Cognitively simple tasks, on the other hand, only require the recall of information from memory or the execution of a simple procedure.

chemistry knowledge whereas the corresponding limiting reagents and dilution procedural items required the participant to integrate all three levels (macroscopic, submicroscopic, and symbolic). This act of integrating the three levels of chemistry knowledge is a conceptual task itself, albeit embedded within a stoichiometric procedural task. In an effort to aid participants in working with proportional reasoning across these three levels, dimensional analysis was taught. Dimensional analysis supports proportional reasoning skills by showing how the units of measure are assigned and transformed during the arithmetic computation of ratios and proportions. But this numerical manipulation is simply a routine to be memorized rather than a way of reasoning through the multiple knowledge levels required by a stoichiometric task. Mechanistic learning of this type has been shown to block reflective competence on the part of the students, leaving them unable to learn from the problems they have done (Hiebert, 1992; Hiebert & Wearne, 1985). Stoichiometry is taught at the pre-college level as a set of tools divorced from use and through the procedure of dimensional analysis. As evidenced by the posttest results, simply re-teaching the dimensional analysis procedure through direct instruction was not effective in promoting stoichiometric procedural competence. Students need to be cognitively engaged with the solution process rationale in order for any possibility of transfer to new situations.

The work of Chi, Bassok, Lewis, Reimann, & Glaser (1989) demonstrated that students who self-explain worked examples learn more than those who tend to them in a more cursory manner. Since most students do not spontaneously provide effective self-explanations when studying worked examples, instruction needs to provide prompts for eliciting them (Renkl, 1997; Renkl, Stark, Gruber, & Mandl, 1998). The explanations should focus on the conceptual understanding of the tripartite nature of chemistry knowledge, not just the process of dimensional analysis. Practice with actual tasks would still be necessary to develop fluidity and accuracy. Therefore, after cognitively engaging students with self-explanations of worked examples, support could be faded gradually from the use of incompletely worked examples to independent problem solving. Renkl and Atkinson (2003) have found that such a backward fading process (starting with last step of a worked example's solution) along with prompts for self-explanations fostered both near and far transfer performance.

5.2 BACKGROUND EXPERIENCES AND CHARACTERISTICS

The fact that gender and SAT scores together (although not their interaction) explained a third of the variability in posttest performance as well as subsumed any treatment effect serves to emphasize the challenge that even instructors at selective institutions face in promoting the learning of chemistry. Furthermore, this relationship between gender and SAT scores may have been recognized by the females in the population with lower SAT scores, as evidenced by their self-selection into this study.

The finding of a relationship between SAT score and gender in the population from which this study's participants were drawn is a complex one that requires further investigation. Although the difference between male and female math SAT scores has declined since 1974, significant differences still exist in math and science content areas at selective institutions. Specifically, female performance exceeds that of males in computational skills but the opposite is true with problem-solving skills (Linn & Hyde, 1989). Very high scores on the math SAT require solving word problems quickly with rapid, intelligent guesses not lengthy computations. The ability to devise or revise procedures depending upon a problem's context, not to mindlessly apply algorithms, also is needed to attain a very high score. In problem-solving courses such as introductory chemistry, gender may be linked indirectly to performance through the math SAT scores. Introductory chemistry courses, as they are traditionally taught, with emphasis on problem solving-skills but reliance on procedural executions such as dimensional analysis, may indeed serve to filter out those students without strong mathematics backgrounds (as measured by the SAT), especially at historically scientific and professional institutions such as CMU (Boli, Allen, & Payne, 1985; Hyde, Fennema, & Lamon, 1990; Linn & Hyde, 1989).[11] As the central science, chemistry in turn serves as the gatekeeper for future study in many other science domains. One way of temporarily supporting students in developing the necessary problem-solving skills would be to encourage their self-study of the OLI course revised with the types of examples and tasks described in section 5.1.2.

5.3 STUDY PRACTICES

Time spent by the participants with the study materials, be they text-based or technology-rich, was not a predictor of stoichiometry learning as measured by posttest performance. Self-allocated time may not have been sufficient for mastery of the procedures and concepts, or simply may not have reflected a continuous engagement of participants with the subject matter. A more helpful consideration may be how to encourage students to optimize what they are doing during their study time.

[11] Tai, Sadler, & Loehr (2005) have found that when male and female testing history is similar, gender is not a factor that influences success in introductory college chemistry.

The literature on identifying predictors for introductory college chemistry success has uncovered both direct and indirect relations to study times. Krajcik and Yager (1987) compared the achievement of high ability students in AP chemistry between those who had completed a year of high school chemistry and those who had not. Although those students who had completed high school chemistry scored higher on the pretest, the two groups performed similarly on the posttest. However, the group without previous chemistry coursework experience spent significantly more hours with tutors to assist with their study of chemistry. The students in this group had to work harder (i.e., spend more time) to perform satisfactorily. Tai, Ward, and Sadler (2006) looked for characteristics of the high school chemistry experience that were associated with student success in introductory college chemistry. Stoichiometry was the only chemistry topic that was an important predictor of college chemistry performance. Those students who experienced stoichiometry as a recurring theme throughout their high school course significantly outperformed those who studied stoichiometry for just a few weeks as an isolated topic. A heavy time emphasis on stoichiometry in the high school course served to support students in the college course in which stoichiometry topics had to be mastered within the first few weeks. Tai et al. (2006) also found that high school calculus, in addition to SAT performance, was even a stronger predictor of college chemistry performance, even though calculus is not utilized in the introductory college chemistry course. This finding points to an indirect effect of study time. Studying calculus in high school increases the likelihood that students possess fluency in algebraic manipulations, the very skills that are necessary for understanding most introductory chemistry lectures and solving the assigned homework problems.

Analysis of the log file data for the technology-rich treatment group has revealed a clue for optimizing the use of allocated study time in the OLI course. Although overall time spent in the course was not related to learning outcomes, nearly 40% of the variability in posttest-2 scores from the technology-rich treatment was related to the degree of participant interaction with the Virtual Lab. Furthermore, the relationship between SAT and posttest-2 scores was subsumed by participant interaction with the Virtual Lab. This finding suggests an opportunity for mathematically less-advantaged chemistry students similar to that of inexperienced chemistry students utilizing tutoring hours in the aforementioned study by Krajcik and Yager (1987). Online chemistry students could be advised that interacting with the Virtual Lab can lead to increased learning by including in the OLI course's instructions what this research effort has discovered. What remains unanswered by this study, however, is how the interactions with the Virtual Lab work to increase participants' learning. Are increased interactions a sign of more practice with solving stoichiometric problems? Or do increased interactions indicate a participant's deeper engagement within a problem such as looking back and forth between a macroscopic flask on the Workbench and the submicroscopic entities and symbolic notations of the Solution Information Table? Or do the interactions reflect exploratory actions by learners as they generate and test self-developed hypotheses?

5.4 CONCLUSIONS

Although most students come to college with remarkable skills for accessing and downloading music from the Internet, few have had experience with using online technologies to optimize their learning in academic areas such as chemistry. The most important finding from this research is that studying stoichiometry through the OLI course is related to increased learning outcomes when its main interactive instructional strategy (Virtual Lab) is accessed and utilized. The instructions for the OLI course could share this research finding with potential users in order to encourage their engagement with the Virtual Lab's problem-solving activities. Furthermore, default navigation options (e.g., *continue* buttons) within the course could lead to Virtual Lab practice. If users choose to bypass this default option, a pop-up reminder message of the benefits of interactive engagement with the Virtual Lab simulation could be displayed.

This study also uncovered a diversity in the level of mathematics preparation of incoming university freshmen at a historically scientific and professional institution. Students with less developed background knowledge will need to be supported temporarily in their early quantitative coursework. One way to provide support would be through online courses or tutorials that focus on foundational skills specific to introductory coursework in quantitative areas such as chemistry. All students should be invited to take advantage of these enrichment opportunities, a technique that may be more effective in promoting their acceptance and use since those in greatest need would not subjected to the stigmatization of assignment to remedial work (Seymour & Hewitt, 1997).

The fact that average posttest scores were mediocre at best suggests the need to both modify and increase the number of the instructional locations (e.g., examples and tasks) in order to promote fluency and flexibility with stoichiometric procedures. Restructuring examples to elicit self-explanations would encourage learners' deeper processing of concepts related to these procedures. This pedagogical move may help to promote the cognitive flexibility needed for transfer to both near (posttest) and far (equilibrium and acid-base chemistry) problem-solving situations. Increasing the number of tasks would support the development of fluency and accuracy by providing more opportunities for practice. Implementation of a backward fading (Renkl & Atkinson, 2003) instructional approach--beginning with incompletely worked examples along with prompts for self-explanation and gradually progressing to independent problem-solving activities--may promote development of both a fluid and flexible knowledge base. Integrating these pedagogical strategies with the dynamic and interactive capabilities of the OLI course may be able to support student learning more effectively than studying from static text-only materials.

The *massification* of tertiary education during the latter half of the past century has resulted in an increased need to support a diverse population of students. The dynamic features of Internet technology can facilitate a pedagogical paradigm shift from the passive dissemination of content (e.g., through textbooks, videos, lectures) to the active support of these learners (e.g., through immediate informative feedback and exploratory environments) as they transform information into meaningful knowledge. Instructors may choose to implement online courseware along with--or even instead of--traditional textbooks as a way of fulfilling this need. But just as textbook review is based on criteria such as content and organization, so to will online courses need to be systematically evaluated to determine if the full potential of the individualized learning resources (e.g., interactive and exploratory environments) has been exploited. The framework developed for analyzing online chemistry courses (Appendix A) in support of answering this study's research questions contributes to such a genre of online course analysis. Central to this framework is an examination of the extent to which the dynamic and interactive features of online technology are implemented in the service of engaging learners as they connect new information to prior knowledge and of scaffolding them as they execute complex tasks, all for the purpose of constructing a flexible and fluent knowledge base.

APPENDIX A

REVIEW OF ONLINE CHEMISTRY COURSES

General chemistry knowledge is a core component of scientific literacy. In addition to being a long-established prerequisite for most of the traditional science, engineering, and medical fields, general chemistry knowledge is a foundation for many modern interdisciplinary pursuits such as forensics, environmental studies, and patent law. A basic chemical understanding also can assist everyday citizens with their personal choices as well as their participation in public policy decisions (e.g., regarding pharmaceuticals, nutrition, waste disposal). Chemistry's ubiquitous presence in so many facets of modern society (Amato, 1991) suggests a need for its instruction to be both learnable and accessible.

General chemistry instruction at the college level typically employs a large lecture format in which the professor defines terms and works through problems while the students take notes. Student questions and investigations are relegated to other time periods such as recitation hours and laboratory periods that may or may not be conducted by the course instructor. More often than not, what is taught does not reflect the valued work of the domain but consists of a compilation of facts and procedures to be learned as preparation for subsequent chemistry coursework, most of which is not pursued except by chemistry majors (Breslow, 2001; Evans, Leinhardt, Karabinos, & Yaron, 2006). This traditional *instructivist* (DiSessa, 2000) paradigm of delivery is incompatible with recent understanding about the *constructivist* nature of cognition. According to research findings from the learning sciences, students construct their own understanding by actively processing incoming information in the service of reorganizing their prior knowledge. This active processing is limited by a cognitive structure that has a finite capacity for processing but a near infinite capacity for storage. During processing, new information is encoded into long-term memory. The context in which this new information is encoded and rehearsed influences its future retrieval and application (Bransford, Brown, & Cocking, 1999). Online instructional delivery systems have the potential to overcome the limitations of traditional classroom lectures by providing students with opportunities for their active engagement and support in the learning process through self-pacing, dynamic expositions, interactive problem solving, and open ended or scaffolded explorations of new information. Online environments can also provide increased access to college-level chemistry education for populations heretofore excluded due to the constraints of time, distance, goals, or money.

The rapid expansion of the World Wide Web across regional, social, and technological barriers positions the Internet to provide both an environment for enhanced undergraduate education and a venue to meet the increased demand for lifelong learning in a global, information-based society. Online courseware promotes a *democratization* of learning by increasing access to higher education by populations otherwise excluded, broadening the range of people served by elite institutions, and supporting those students who need additional learning opportunities to keep on track (Larreamendy-Joerns & Leinhardt, 2006). The unregulated and unstructured nature of the Web, however, means that users will need to decide which opportunities are appropriate to access, that is, to identify which online courses will optimize their learning experiences.

A variety of online instructional materials for chemistry has been developed and disseminated by chemistry professors, high school teachers, textbook publishers, museums, and even chemistry students. Several of these resources can serve as stand-alone general chemistry courses that are equivalent in content coverage to that found in an introductory college chemistry textbook, the traditional foundation of general chemistry instruction. What is needed, however, is a framework by which users can ascertain the effectiveness of a given online chemistry course. The goal of this paper is severalfold: to build upon and refine a framework for analyzing online courses; to test this framework's utility by analyzing online chemistry courses; and to contribute to our understanding of online chemistry instruction.

Existing Frameworks

Other researchers have endeavored to examine and evaluate online instruction. Nachmias and his associates (Mioduser, Nachmias, Lahav, & Oren, 2000; Nachmias & Tuvi, 2001; Tuvi & Nachmias, 2001; Tuvi-Arad & Nachmias, 2003) have created a taxonomy consisting of five dimensions of pedagogical and technological characteristics, such as how knowledge is represented, communication and navigation methods, and the scope of content. Using this classification scheme they analyzed 95 atomic structure websites and found that the overall chemistry content presented was reliable. Graphical tools or advanced communication means rarely were incorporated into the courseware, however, so that the content delivery of the websites resembled online versions of textbooks rather than interactive learning environments. The descriptive, categorical nature of this five-part taxonomy facilitates its application to areas other than chemistry. What is missing, however, is an analytic tool that measures the cognitive quality of instructional materials—the features of course design that promote meaningful learning.

Another approach to analyzing Web-based instruction was developed by Larreamendy-Joerns, Leinhardt, and Corredor (2005) who extended Cobb's (1987) evaluative framework of statistics textbooks to online instructional materials for statistics. Like Cobb, they focused on the quality of explanations as exemplified by the extent to which instruction relied upon formulas versus underlying principles, and on the quality of practice opportunities in terms of authenticity and cognitive demand levels. In addition, they examined and evaluated the quality of interactivity afforded by current technologies--dynamic representation and feedback. Their analysis found that there was a concerted effort by most courses to support conceptual understanding as well as procedural practice through visualizations and carefully unpacked explanations. Although some courses had come a long way from traditional textbooks through extensive use of hyperlinks and enhanced representation, there was still an inadequate level of adaptive feedback and scaffolding to meet individual users' needs. Unlike the descriptive nature of the Nachmias taxonomy, however, this analytical framework provides a tool by which to compare the cognitive quality of online courses.

Analyzing Online Chemistry Courses

This paper reports on the development and testing of a framework for analyzing online chemistry courses. Chemistry was chosen as a domain for examination because chemistry knowledge is foundational to many of the socioeconomic concerns of a modern society (e.g., pollution, pharmaceutical therapies, genetic engineering) and because many aspects of chemistry are hard to learn. What makes chemistry hard to learn? As with other sciences it has a unique and specialized language and relies on mathematical manipulations. But students see enactments of chemistry happening all around them--fireworks explode to produce colorful and noisy displays on summer nights, water freezes creating both perilous footing and exciting arenas for competitive sports, fermenting vats of grain produce beverages to enliven social encounters as well as to fuel the vehicles bringing the partygoers together. What makes chemistry hard to learn and to understand is that these macroscopic features that the students experience are emergent properties resulting from actions at an atomic or molecular level (Chi, 2005; Chi & Roscoe, 2002; Penner, 2000). These submicroscopic actions operate at a non-human scale and are unable to be directly manipulated. As a result, developing an intuition for connecting the macroscopic features with submicroscopic actions is difficult (Yaron, Leinhardt, & Karabinos, 2004). Still another challenge for learners is mastery of the representational system of symbols, formulas, equations, and mathematical manipulations used to describe and explain the submicroscopic interactions that give rise to the macroscopic features. Expert chemists move freely among the three levels (macroscopic, submicroscopic, and representational) as they pursue their work, including that of instruction (Johnstone, 2000). But students, whose knowledge framework is rudimentary at best, have great difficulty understanding their teachers when explanations move away from the macroscopic level with which they have everyday experience. Level-specific explanations for the same phenomenon can be frustrating to students as well as interfere with their learning (Scerri, 2000).

The integration of multiple levels of knowing and subsequent difficulty in learning chemistry presents an instructional challenge that online technology may be well equipped to address. A multimedia platform, which includes interactive simulations by which the invisible can be made visible as well as provisions for scaffolding of and timely feedback for student problem solving, should be able to support active learning in a complex and abstract domain such as chemistry. An effective analytical framework to assess the quality of such online chemistry instruction would ascertain whether a given online course integrates the distinctive features of modern technology with instructional strategies informed by research on the constructivist nature of cognition.

Selection of an Instructional Topic

An important consideration for the examination of online chemistry courses is the selection of an instructional focus as the location for analysis. The chosen topic should be one that finds frequent application throughout the domain as well as in related areas for which general chemistry is a prerequisite. Furthermore, this topic should be challenging for students to learn and preferably a locus of previous educational research. Stoichiometry is such a topic. It is taught during the high-school chemistry course as a collection of procedures but requires both procedural and conceptual applications in subsequent studies of solution equilibrium in college chemistry, materials and energy balance in engineering, and biogeochemical interactions of ecosystem processes. Stoichiometry embodies what it is about chemistry that is hard to learn. Stoichiometry is the chemical algebra that connects the macroscopic features with the submicroscopic interactions of the domain by using a set of abstract symbols and relying on the formal reasoning of proportional analysis. For more than 50 years chemical educators have been seeking explanations and solutions for the difficulty that many students exhibit with this aspect of chemistry instruction (Gabel & Bunce, 1994).

Selection of Instructional Locations

Much of the understanding that we have about how new information is processed by learners comes from research in areas that are rich in formal mathematical procedures undergirded by an abstract conceptual base: physics, algebra, computer programming. Since stoichiometry is of a similar nature, findings from that research is helpful in guiding the development of a framework for examination and evaluation of online chemistry courses. Specifically, the analysis uses a framework that focuses on the *examples*, *tasks*, and *distinctive features* provided by online chemistry courses.

Examples are essential elements of instructional explanations. Examples can introduce a concept by allowing the learners to connect their prior knowledge to the new information, can function as boundaries of concepts, can serve as templates for organizing domain knowledge, and can afford the bases for inductive generalization (Rissland, 1991). For newly learned concepts and procedures to be flexible, that is, able to be applied to multiple situations within the domain of study, students need experience with multiple and varied examples in different contexts from which they can extract the critical underlying principle(s) (Perkins & Salomon, 1989; Quilici & Mayer, 1996).

Tasks provide another location for knowledge construction. Multiple practice opportunities with tasks that cover a range of situations are necessary for improved performance in problem solving (Rosenbaum, Carlson, & Gilmore, 2000). Practice enables learners to become proficient at completing tasks by increasing their speed and accuracy (Anderson, 1993). Practice with authentic tasks (Chinn & Malhotra, 2002) supports the construction of meaningful connections within the learners' chemistry knowledge base (Clark & Mayer, 2003). Together with authentic examples, authentic tasks elaborate the problems and issues that matter to the discipline and provide students with a vision of what it means to *do chemistry*.

The *distinctive features* of online technology include abilities to dynamically represent abstract information, to provide timely feedback, and to scaffold the execution of complex tasks. Representations support instructional explanations (Leinhardt, 2001) in that they help learners to visualize knowledge relationships rather than to focus on individual pieces of information (Larkin & Simon, 1987). Dynamic representations with interactive capabilities can provide timely feedback (implicit or explicit), a critical component of effective learning environments (Bangert-Drowns, Kulik, & Kulik, 1988). Other interactive learning objects such as simulations and cognitive tutors can scaffold the high cognitive loads inherent to complex problem solving (Van Merrienboer, Kirschner, & Kester, 2003). Dynamic representations and interactive opportunities support a *constructivist* environment by engaging learners in revision of and building on their current understandings through participation in authentic disciplinary activities, exploration, and reflection.

Method

Selection of Online Courses

An Internet search of available online courseware to find a suitable sample was guided by several criteria. First, the chosen courses needed to be supported by both MAC and PC platforms so that they were accessible to vast audiences. Second, the courses needed to address those stoichiometry competencies that were of conceptual difficulty to beginning chemistry students and of disciplinary importance to the understanding of chemical equilibrium, a major focus of second-semester introductory college chemistry. The following three topics met those criteria: limiting reagents (or reactants); molarity; and dilution. Third, at a minimum for each of the aforementioned topics, the courses needed to include explanations of the content with worked examples of procedures and practice tasks. Fourth, the courses had to be amenable to self-study without requiring the intervention of an instructor. Courses that met these four criteria were sought from a variety of sources: general support websites and specific course companion websites as well as commercial ventures such as textbook companion websites or stand- alone CD-ROM courses not specifically affiliated with a textbook or institutional class. The following online materials were selected:

1. Grandinetti's General Chemistry Lectures (http://www.chemistry.ohiostate.edu/~grandinetti/teaching/Chem121/lectures/)
2. Student Website for Chemistry: The Science in Context (http://www.wwnorton.com/chemistry/home.htm)
3. Thinkwell Chemistry (www.thinkwell.com)
4. General Chemistry Interactive CD-ROM, Version 3.0 (ISBN: 0-03-035319-X)
5. Open Learning Initiative Chemistry (http://www.cmu.edu/oli/courses/enter_chemistry.html)

Course Descriptions

Grandinetti's General Chemistry Lectures (OSU) is authored by Philip Grandinetti, Professor of Chemistry at Ohio State University, Columbus, OH. He created this website for Chemistry 121, the first general chemistry course for science and engineering majors. In addition to lecture notes the site includes PDF files of old quizzes and exams as well as links to related science websites such as periodic tables. Each lecture presents explanations and worked examples in text format. Practice problems are located at the end of each topic presentation via a link to the Ohio State University Undergraduate Chemistry website (http://lrc-srvr.mps.ohio-state.edu/). Stoichiometry topics specified by our selection criteria were found in Lecture 6 within the topics of *Limiting Reagents* and *Solution Concentration and Stoichiometry*. The website is free of charge and can be accessed on both PC and Mac OSX platforms.

The Student Website for Chemistry: The Science in Context (NORTON) is produced by April Lange, the science media editor at W.W. Norton & Company. The company created this website as an online resource for the college textbook, *Chemistry: The Science in Context* (Gilbert, Kirss, & Davies, 2003) that it publishes. Organized by corresponding textbook chapters, the website offers summaries of the chemical principles introduced, worked examples of key equations and concepts, animated tutorials that include practice exercises with hinting and feedback, crossword puzzles of new vocabulary, and multiple-choice quizzes with answer feedback. Stoichiometry topics specified by our selection criteria were found in Chapter 4 (*Stoichiometry and the Formation of the Earth*) and in Chapter 5 (*Solution Chemistry and the Hydrosphere*). The website is free of charge and can be accessed on both PC and Mac OSX platforms.

Thinkwell Chemistry (Fall, 2001 edition) (THINKWELL) is produced by the Thinkwell Corporation, Austin, Texas. Chemistry professors Dean Harman (University of Virginia), Tarek Sammakia (University of Colorado), and Gordon Yee (Virginia Tech) have authored and provided first-year college chemistry lectures accompanied by graphics and animations on ten CDs. A password-protected companion website offers transcripts of the lectures, companion notes, interactive quizzes with feedback, and external links to related chemistry websites. Stoichiometry topics specified by our selection criteria were found in Chapter 3 (*Stoichiometry*) and in Chapter 4 (*Reactions in Aqueous Solutions*). The cost is $101.95 which includes the CD's, access to the companion website, and shipping. To run the CDs. the minimum system requirements for a PC are a Pentium (166 MHz or faster) processor with Windows 95, 98, NT 4.0 or later. Minimum requirements for a Macintosh are a Power PC (120 MHz or faster) processor with Mac OS 8.1 or later, and 32 MB RAM. It should be noted that Classic Mode must be installed on OSX machines.

General Chemistry Interactive CD-Rom (Version 3.0) (GENCHEM) is distributed by Thomson Learning, Stamford, Connecticut. Co-authors are chemistry professors William J. Vining (University of Massachusetts, Amherst) and John C. Kotz (State University of New York, Oneonta), along with Patrick Harman. *General Chemistry Interactive* is an all-inclusive stand-alone first year college chemistry course (virtual textbook) delivered on two CDs. Each chapter consists of multiple topics assigned to a screen. The screens are made up of multiple layers that at a minimum include an *outline* or overview layer and a *description* layer. The description layer gives a multimedia presentation of the screen topic using video and animation. There are other layers that may be included: *exercises*, which are movie clips or detailed graphic images along with questions in support of detailed examination of what is presented; *simulations*, which are models of a theoretical system or experiment accompanied by a series of questions to help the learner navigate through the simulation; or *tutorials*, which are interactive question-and-answer sessions in support of a particular problem solving procedure(s). Topics specified by our selection criteria were found in Chapter 4 (*Chemical Equations and Stoichiometry*) and Chapter 5 (*Reactions in Aqueous Solution*). The price is $37.76 plus $6.20 shipping from Thomson Learning (www.thomson.com). Minimum system requirements for a PC are a Pentium Class processor with Windows 98/NT, 64 MB RAM/8x, 16-Bit color (800 x 600). Minimum requirements for a Macintosh are OS 8.5.1+ Power Mac with 64 MB RAM/8x with thousands of colors (800 x 600). It should be noted that Classic Mode must be installed on OSX machines.

Open Learning Initiative Chemistry (OLI) is one of several introductory college courses developed by Carnegie Mellon University's Open Learning Initiative (http://www.cmu.edu/oli/index.html), a collaboration of cognitive scientists, experts in human computer interaction, and content area faculty. The project is funded by a grant from The William and Flora Hewlett Foundation. Chemistry professor David Yaron is the lead developer of the OLI Chemistry course that is designed for review of stoichiometry principles. Course features are based upon well-confirmed principles of cognitive theory that include learning environments to engage the students in active learning practice with frequent opportunities for feedback, mental scaffolding that supports students' knowledge construction, and the integration of contextual knowledge to enhance transfer of learning to contexts outside of the teaching environment. The OLI Chemistry course is situated in the real-world problem of arsenic contamination in Bangladesh's water supply. The course offers a variety of learning experiences including video expositions, text, simulation activities in the Virtual Lab, and tutors to support the integration of declarative and procedural knowledge. Topics specified by our selection criteria were found in Module 5 (*The Basic Tools of Stoichiometry*), Module 6 (*Testing Water for Arsenic Contamination*), Module 7 (*Using Density to Check Arsenic Contamination*), Module 8 (*Arsenic Remediation*), and Module 12 (*Limiting Reagents*). All of the Open Learning Initiative courses, including chemistry, are openly available and free to the public. Academic credit is available only through academic institutions. The chemistry course can be run on both PC and Mac OSX platforms.

Tabulation of Course Resources

Computers provide a multitude of possibilities for captivating students, as evidenced by their fascination with computer games, Web-surfing, and even hacking. What is so promising about online courses are not the technological resources per se, but the engagement and interaction they enable (DiSessa, 2000). Just as calculators are an improvement over slide rules for ease, speed, and scope of problem solving they facilitate, so too can the dynamic resources of online delivery activate the information heretofore relayed through static textbooks or passive lectures. Therefore the online course resources were classified according to function: organization, content delivery, practice, and interactivity. *Organizational* resources support learners in managing their learning activities. For example, a course map facilitates non-linear navigation. *Content delivery* resources include the modes by which information is represented. For example, students may be able to access verbal explanations either through text or audio. *Practice* resources refer to the type of responses solicited from the student in the execution of tasks and are reflective of cognitive engagement. For example, students may be asked to either select (multiple choice) or to construct (short answer) a response. *Interactive* resources are those learning opportunities, such as feedback, specifically facilitated by computer technology. For example, feedback to a practice opportunity may involve a simple confirmation of accuracy, a series of supportive hints, or an extensive explanation of the worked-out solution. Because the nature and extent of course resources may influence what gets explained and how it is explained, we counted the types and number of resources for each course.

Coding and Analysis of Instructional Locations

Segments from each of the five courses that addressed the stoichiometry areas of limiting reagents, molarity, and dilution were analyzed. These stoichiometry areas were selected for review based upon their disciplinary applications in equilibrium chemistry and their conceptual difficulty for beginning chemistry students. The level of cognitive effectiveness among these courses was compared by examining the quality and quantity of *examples*, the quality and quantity of *tasks*, and the implementation of *online features* such as visualization and interactivity.

Examples

Coding. For coding purposes an example was defined as a specific illustration of a concept or procedure. We identified five categories of examples that ranged in cognitive demand from the cursory application of a procedure to its authentic use in real-world scenarios. Cognitively shallow examples were those in which a cover story was minimal or lacking, a chemical formula or equation was presented along with given quantities, a single outcome was required, and the calculation process was emphasized. Two categories of examples reflected this approach: cryptic procedural (CRP) and alternative procedural (ALP). An example was coded as CRP if one solution path to the outcome was explicated. If more than one solution path was explicated, the example was coded as ALP. The following CRP example is from OSU (Lecture 6):

What is the molarity of a solution prepared by dissolving 8.0 grams of NaOH in H_2O so that the final volume is 250 mL?

$$8.0\text{ g NaOH } = \frac{1\text{ mole NaOH}}{40.0\text{ g NaOH}} = 0.20\text{ moles NaOH}$$

Then calculate the molarity

$$\frac{0.20\text{ moles NaOH}}{250\text{ mL}}\ \frac{1000\text{ mL}}{1\text{ L}} = 0.80\text{ M NaOH}$$

The following ALP example is from NORTON (Chapter 5).

How many grams of $AlBr_3$ are required to make 500.0 mL of 0.20 M $AlBr_3(aq)$?

Solution: Method 1

$$M = \frac{\text{mol solute}}{\text{L solution}} \qquad \text{Solute} = AlBr_3 \qquad \text{Solution} = 500.0\text{ mL}$$

$$500.0\text{ mL } \frac{1\text{ L}}{1000\text{ mL}} = 0.5000\text{ L}$$

$$0.20\text{ M} = \frac{\text{mol } AlBr_3}{0.5000\text{ L}}$$

$$\frac{0.20\text{ mol}}{\text{L}} \times 0.5000\text{ L} = 0.10\text{ mol } AlBr_3$$

molar mass of $AlBr_3 = 26.982 + 3(79.904) = 266.694$ g/mol

$$0.10\text{ mol } AlBr_3 \times \frac{266.694\text{ g}}{1\text{ mol}} = 27\text{ g } AlBr_3$$

Solution: Method 2

0.20 M can be interpreted as 0.20 mol $AlBr_3$ in 1L solution

$$500.0\text{ mL solution} \times \frac{1\text{ L}}{1000\text{ mL}} \times \frac{0.20\text{ mol } AlBr_3}{1\text{ L}} \times \frac{266.694\text{ g}}{1\text{ mol}} = 27\text{ g } AlBr_3$$

In contrast to these two cognitively shallow example types, three categories of examples were considered to be cognitively deep since they may serve to facilitate knowledge organization by the learner: connected to everyday (COE), connected to chemistry (COC), and authentic problems (AUP). An example coded as COE attempts to connect stoichiometry concepts and/or procedures to students' everyday experiences, as reflected in the following transcript of a lecture movie from THINKWELL (Chapter 4). Note that cranberry juice is an everyday example of a solution for which the concentration of a particular solute, sugar, can be described numerically.

I just poured myself a glass of cranberry juice. Now, on the bottle I found, to my surprise, that there is 40 grams of sugar per serving. What is that, 40 grams per 8 ounces? That's a unit of concentration. That reduces to five grams per ounce. Five grams of sugar for every ounce of solution. Right?...I almost missed something. I mentioned that this is grams per ounce. That's not a unit that chemists normally use. Chemists most of the time will use moles per liter. In fact, we've defined molar as moles of solute per liter of solution. This again is a more convenient unit for us because it talks about amount of material in terms of numbers of particles, rather than mass of particles, or mass of materials.

An example coded as COC related the current topic under study to previously or to-be-learned concepts or procedures as reflected in the following example from NORTON (Chapter 5). The process of titration (heretofore unaddressed) was used in this example to determine the molarity of an unknown solution. Molarity is the stoichiometric topic being explicated. The topic of titration will be studied in depth when acid-base chemistry is addressed later in the course.

What is the molarity of a solution of hydrochloric acid, if 0.1511 g of sodium carbonate in 100.0 mL of water required 27.31 mL of the acid solution to reach the equivalence point?

$$HCl + Na_2CO_3 \rightarrow NaCl + H_2O + CO_2$$

Solution:

Before solving any stoichiometry problem, make sure the reaction is balanced. In this example, it is not. Balancing the reaction give you

$$2\ HCl + Na_2CO_3 \rightarrow 2\ NaCl + H_2O + CO_2$$

Because this example asks you to find molarity (a formula or relationship) as your final answer, it is useful write the formula and see what you have and what you need to find.

$$M = \frac{\text{mol solute}}{\text{L solution}}$$

Since it is moles of hydrochloric acid solution, HCl is your solute. Looking closely at the question, you will also notice that the volume of HCl solution is given as 27.31 mL. Since you need volume in liters for use in the formula

$$27.31\ \text{mL} \times \frac{1\ \text{L}}{1000\ \text{mL}} = 0.2731\ \text{L}$$

Now all you need is the moles of HCl. No further information is given directly about HCl, however information (grams) is given about sodium carbonate and that can be related to HCl from the chemical reaction

$$0.1511\ \text{g}\ Na_2CO_3 \times \frac{1\ \text{mol}\ Na_2CO_3}{105.99\ \text{g}} \times \frac{2\ \text{mol HCl}}{1\ \text{mol}\ Na_2CO_3} = 2.851 \times 10^{-3}\ \text{mol HCl}$$

Note that step 4 was not needed [A reference to general rules suggested earlier in the lesson for solving stoichiometry problems], because the desired unit was moles! Now there is sufficient information to use the formula

$$M = \frac{\text{mol}}{\text{L}} = \frac{2.851 \times 10^{-3}\ \text{mol}}{0.273\ \text{L}} = 0.1044\ \text{M}$$

Note that the volume of water was not used in these calculations. It is not a reactant, nor does it affect the moles of sodium carbonate, nor was it part of the HCl solution which the question asked about. It is not usual to have extra information in problems of this type.

An example coded as AUP was situated in laboratory work or in a real world scenario. A reasonable description of the setting makes the example both understandable and engaging to the learner who must reason from presented data. The following AUP example from GENCHEM (Chapter 5) describes an authentic activity in a chemistry laboratory, the making of a solution of specified molarity. An audiovideo clip of the process was an integral part of this example.

It is important for a chemist to have the technical skill to prepare solutions with known concentrations. Let's say we wish to prepare 250 mL of a 0.140-M solution of $NiCl_2 \cdot 6\,H_2O$. We begin the process by determining the amount of solute to use. First we calculate the number of moles needed for the solution:

$$\text{Moles } NiCl_2 \cdot 6\,H_2O = \frac{237.7\text{ g } NiCl_2 \cdot 6\,H_2O}{1\text{ mol } NiCl_2 \cdot 6\,H_2O} = 8.32\text{ g}$$

Next we translate the moles into mass in grams ($NiCl_2 \cdot 6\,H_2O$ has a molar mass of 237.7 g/mol):

$$0.0350\text{ mol } NiCl_2 \cdot 6\,H_2O\ \frac{237.7\text{ g } NiCl_2 \cdot 6\,H_2O}{1\text{ mol } NiCl_2 \cdot 6\,H_2O} = 8.32\text{ g}$$

Next we prepare the solution using a 250-mL volumetric flask

Note: An audio-visual now demonstrates the actual laboratory technique for making the solution.

Analysis. Both the quantity and variety of examples are important since comparison of multiple examples enables students to distinguish relevant from incidental features of specific problem types. The total number of examples in each course for each target topic were counted as were the number of each type of example (e.g., CRP, ALP, COE, COC, AUP) across the target topics for each course. A random selection of 25% of the examples was coded for reliability by an independent coder. Overall reliability was 100%. Example-type frequencies were transformed to percentages relative to the total number of examples for each course across target topics. Since both the quantity and quality of examples are important conditions for learning from them, we ranked each course according to both criteria. The mean number of examples per course across target topics was calculated. Since complex examples provide more opportunities for engagement and encoding than algorithmic-type examples, a complexity index was calculated based upon the proportion of each course's examples that were coded as either connected to chemistry (COC) or authentic problems (AUP). We did not include connected to everyday (COE) examples in the measure of complexity because in the few instances in which they were used, they were not fully unpacked, focusing more on surface rather than underlying features of the concept being explicated. For each course the mean number of examples across topics was plotted against its complexity index.

Tasks

Coding. For coding purposes, a task was identified as a specific activity that must be completed by the learner in the service of practice and/or knowledge assessment. We identified five categories of tasks that ranged in cognitive demand from simple recall of facts or definitions to real-world problems with no defined solution path. Cognitively simple tasks were those in which students needed to recall (REC) information from memory or to execute a simple procedure (SPR). The following REC task is from NORTON (Chapter 4). The task requires that the student select the definition of a limiting reactant from several choices.

The limiting reactant is
(a) the substance you run out of first
(b) the reactant that determines the amount of product
(c) the substance left over
(d) both a and b
(e) both b and c

The following SPR task, from OSU (Lecture 6), requires that the student apply a well-rehearsed procedure removed from the context of any real problem situation for which the procedure would have meaning.

Determine the number of moles of solute present in 455 mL of 3.75 M HCl solution. (Atomic weights: Cl = 35.45, H = 1.008).
(a) 1.56
(b) 1.89
(c) 1.98
(d) 1.71
(e) 1.23

In contrast to these two cognitively simple task types, three types of tasks were considered to be cognitively complex since they may support incorporation of new knowledge into, reorganization of, and strengthening of connections within, the learner's cognitive structure: complex procedural (CPR), conceptual (CON), and authentic problem solving (AUT). A task coded as CPR required the integration of two or more procedures. At least one of these procedures would have been taught at a different time during the course or would have been addressed in a previous course. The following CPR task from GENCHEM (Chapter 5) requires that the students apply their prior knowledge of a compound's elements ratio to the calculation of an individual element's molarity in a solution of the compound.

A solution is made by dissolving 24.3 grams of aluminum chloride, $AlCl_3$, in enough water to make exactly 250 mL of solution. What is the concentration (molarity) of the following in mol/L?

- $AlCl_3$
- Al^{3+}
- Cl^-

A task coded as CON involved reasoning without algorithmic procedures. The task itself may or may not use numerical data as reflected by the following two tasks: The first task is from NORTON (Chapter 5). It was coded as CON because it required students to reason about the submicroscopic principles on which the concept of molarity is based—that is, that atoms react on a collective, not mass, basis. The second task is from THINKWELL (Chapter 4). It was coded as CON (even though numerical quantities are given) because it required the coordination of the ratio of elements in a chemical formula with their relative concentration in a solution. The given mass quantity is a distractor.

Why do you think it is important to use molar concentration in chemistry, rather than simply using amounts that are readily determined in the lab, such as g/mol?

Suppose 26 g of calcium chloride $CaCl_2$ (110.98 g/mol) are dissolved in water to make 200 mL of solution. How many times greater is the molarity of chloride ions (Cl^-) than the molarity of calcium ions (Ca^{+2}) in the solution? (choose one)

- .50
- 1.2
- 1.8
- 2.0

A task coded as AUT was situated within the context of the laboratory or real life; such a task may not have a set solution path. An AUT task may include questions in support of reasoning about a simulation activity or a movie demonstration.[1] The following task from OLI (Unit 1, Module 6) was coded as AUT since the cover story is a real-world problem for which necessary stoichiometry tools have been explicated but a solution path not defined. Furthermore, students must make an evaluation after completing the necessary calculations.

According to the WHO, the recommended limit for arsenic in drinking water is 10 micrograms per liter. While it is not easy to answer if a well is toxic or not, a simpler question that can be answered is: Is the concentration of arsenic larger than the WHO recommendation? If so, we may consider toxic this water source. If not, we may say that it is arsenic-wise safe to drink this water. Given that $[AsO_2^-] = 1.123 \times 10^{-6}$ M for a sample of drinking water (represented in a Virtual Lab simulation activity), is this water safe to drink?

Analysis. Multiple opportunities for practice with a variety of tasks can support the development of the fluidity and flexibility needed for problem solving. The total number of tasks in each course for each target topic were counted as were the number of each type of task (e.g., REC, SPR, CPR, CON, AUT) across the target topics for each course. A random sample of 25% of the tasks was coded for reliability by an independent coder. Overall reliability was 90%. Task-type frequencies were transformed to percentages relative to the total number of tasks for each course across target topics. Since both the quantity and quality of tasks are important conditions for learning from them, each course was ranked according to both criteria. The mean number of tasks per course across target topics was calculated. Since complex tasks provide more opportunities for engagement and encoding than simple recall or algorithmic tasks, a complexity index was calculated based upon the proportion of each course's tasks that exhibited complex procedures (CPR), conceptual reasoning (CON), or authentic problem solving (AUT). For each course, the mean number of tasks across topics was plotted against its complexity index.

Online features

Coding. The types of dynamic and interactive learning objects within an online course are an indicator of its cognitive potential. Web-based resources can promote engagement and interaction and multimedia resources allow for the construction of complex meaning independent of text (DiSessa, 2000). Learning objects were classified according to their function: computation, information retrieval, assessment, tutorial, or exploration. *Computational*

[1]When simulations are exploratory in nature learners are able to design their own tasks unbounded by performance standards. Specific consideration of exploratory opportunities is addressed in the *Results and Discussion* section (*Exploratory Environments).*

objects simplify algorithmic procedures and thus reduce cognitive load during complex tasks. An example of a computational object from GENCHEM is the molar mass calculator where students enter the correct formula of a compound and the applet performs the addition of the appropriate atomic weights of the compound's constituent elements. *Information retrieval* objects serve as repositories of facts and data. An example of an informational object from NORTON is the interactive periodic table where students click on a given element to obtain its physical and chemical data. *Assessment* objects include tasks such as multiple-choice or short-answer questions that provide feedback to learners regarding their current knowledge state. *Tutorial* objects incorporate feedback and coaching in the practice of specific procedures. An *exploratory* object, or simulation, is a model of a real or theoretical system that contains information on how the system behaves. By changing parameters to test how a change of input affects output, learners may build conceptual understanding of complex processes. An example of such an exploratory object from OLI is the Virtual Lab in which students manipulate a macroscopic substance on the simulated *workbench* and observe the effects on the substance's submicroscopic molecular composition by its mathematical representation on the *solution information table*.

Interaction with dynamic learning objects without the benefit of feedback is unproductive for students. Immediate feedback both supports thought processes and minimizes the time wasted exploring incorrect paths or recovering from errors (Anderson, Boyle, & Reiser, 1985). *Confirmatory* feedback encourages desired performance. However, the results of studies of the effect of *elaborative* feedback (e.g., explanations for correct or incorrect answers, location and type of errors, Socratic questioning) on learning are inconsistent (Mason & Bruning, 2001; Mory, 1996). It may be that characteristics of learners such as self-efficacy and motivation interact with the type of feedback presented or that too much feedback results in cognitive overload. What may be critical to learning from feedback, then, is how the learners use it rather than the specific properties of the feedback itself. *Informative* feedback provides strategic information such as hints and adaptive measures for the purpose of guiding learners through successful task completion much like human tutors who provide a correct response only when learners cannot be supported otherwise (Narciss, 2004). Whether or not learners can make the appropriate decision to access feedback appears to be related to their prior knowledge of the topic at hand. Lee and Lee (1991) compared the learning outcomes from program and learner control in an online chemistry lesson. They found that program control was more effective during initial stages of learning and learner control was more effective at later stages. Since the location, type, and control of feedback in a course are indicators of its cognitive quality, we coded feedback in each course as to its location (activities), type (confirmatory, elaborative, informative), and control (program or learner).

As a computerized model of a system that can be explored by changing the values of input variables and observing the change in values of output variables, a simulation affords learners opportunities to discover relationships among phenomena whereas hypertext and/or illustrations (static or dynamic) expose these relationships already formed. As a cognitive tool, a simulation facilitates discovery learning by grounding conceptual understanding in the action of a situation. De Jong and Van Joolingen (1998) have reviewed the research on discovery learning with simulations. Studies that compare exploratory with expository teaching provide evidence that discovery-learning results in deeply processed knowledge that is more intuitive and qualitative in nature. Other studies suggest that successful discovery learning is related to the prior knowledge base of the learners with regard to general skills such as hypothesis generation and adaptation based upon data gathered, as well as domain-specific skills. These findings suggest that simulations as exploratory opportunities may need to provide instructional support to guide the learners' discovery processes. Therefore we described the exploratory learning objects' design features as having (1) a directed focus on a singular operation resulting in a simple outcome representation or, (2) a non-directed focus on authentic operations resulting in multiple types of data representations.

Analysis. The level of pedagogical implementation of online technology among the courses was estimated by counting the different types of dynamic and interactive learning objects; by identifying the location, control, and type of feedback opportunities; by comparing the types of scaffolded practice in problem solving; and by evaluating the use of simulations as exploratory learning objects.

Results and Discussion

Course Resources

Table 1 summarizes the resources available in each course. The resources are grouped according to their function: organization, content delivery, practice, and interactivity. Overall, OSU has the fewest number of resources and THINKWELL provides the most. All of the courses include a course map for navigation and some sort of text delivery of content. All but OSU provide interactivity through applets and two types of feedback. Surprisingly, none of the courses provides learning objectives to inform the users of the scope and expectation of performance upon completion of the course. Although objectives may have been formulated by the course designers in order to guide the development process, making users aware of them is important so that students can monitor the state of their learning. Explicit learning objectives play an especially crucial role in online instruction since a human teacher is not available to provide them. The cognitive quality of the content, the practice, and the interactive resources will be addressed in the following sections on examples, tasks, and online features.

Table 1
Available Online Resources per Course

	Course				
Resources	OSU	NORTON	THINKWELL	GENCHEM	OLI
Organizational					
Learning objectives					
Course map	x	x	x	x	x
Record keeping			x		
Periodic table		x	x	x	
Calculator		x	x[5]	x[5]	
Content delivery					
Text	x	x	x	x	x
Static visuals		x	x	x	x
Videos			x	x	x
Audio			x	x	x
Glossary		x	x		

External links	x		x		
Practice opportunities					
Qualitative MC[1]			x	x	x
Quantitative MC	x	x	x		x
Qualitative SA[2]		x			x
Quantitative SA		x		x	x
Interactivity					
Applets		x	x	x	x
Simple feedback[3]	x	x	x	x	x
Complex feedback[4]		x	x	x	x

[1] Multiple-choice format
[2] Short-answer format
[3] Correct/Incorrect and/or correct answer only
[4] Hints, worked out solutions and/or explanations
[5] Not an all purpose calculator but one that calculates molar mass and molarity when given a formula

Examples

For examples to serve as effective learning supports they need to span a range of conditions and there needs to be more than one of them (Gick & Holyoak, 1980, 1983; Quilici & Mayer, 1996). Since construction of structure-based problem schema has been shown to be a fundamental component of mathematical problem-solving expertise (Chi, Feltovich, & Glaser, 1981), exposing students to multiple examples may be necessary for construction of schemas for solving limiting reagent, molarity, and dilution problems. Developing a competency for handling unique or unusual problems also requires the opportunity to see a rich variety of examples. Table 2 displays the number of examples by target topic for each course. Both OSU and THINKWELL provide only one example for dilution and OLI provides only one example for limiting reagent. NORTON provides the most examples overall.

Table 2
Number of Examples by Topic and Course

	Course				
Topics	OSU	NORTON	THINKWELL	GENCHEM	OLI
Limiting reactants	2	6	3	5	1
Molarity	3	8	2	2	2
Dilution	1	4	1	2	2
Total	6	18	6	9	5

Figure 1 shows the frequency of examples in each level of cognitive demand for each course summed across the three topics analyzed. More than half of the examples for OSU and NORTON are cognitively simple (coded as *cryptic procedural* or *alternative procedural*). Cognitively simple examples do not show knowledge in use and are likely to promote memorization of procedures detached from their conceptual underpinnings. In contrast, the majority of the GENCHEM and OLI examples are cognitively complex (coded as *connected to chemistry* or *authentic problem*). Half of the THINKWELL examples are cognitively complex in nature. All of THINKWELL's cognitively complex examples are identified as *authentic problems* (AUP); none is identified as simply *connected to chemistry* (COC). A COC example explicitly relates the current topic under study to previously or to-be-learned concepts or procedures, but not in the service of solving a real world problem. Since an AUP example is situated in the real world or laboratory, by definition it relies upon the integration of multiple concepts and procedures during solution implementation. For example, in a THINKWELL lesson (Chapter 4), an AUP example describes the creation of a 200-milliliter Na_2SO_4 (sodium sulfate) solution from 26.42 grams of sodium sulfate and water. The role of formula weight and significant figures in this process is highlighted. After the solution is created, its molarity (concentration) is computed. Then the concentration of each ion (Na^{+1} and SO_4^{-2}) is determined by using these ions' stoichiometric ratio in the solute. In a subsequent AUP example the program explicates how to determine the volume of this same solution needed to make 250 milliliters of a specified dilution. Creating and diluting stock solutions are activities common in chemistry laboratories. Not only are these two AUP examples connected to each other but also within each of them there are several connections made explicitly to previous chemistry knowledge.

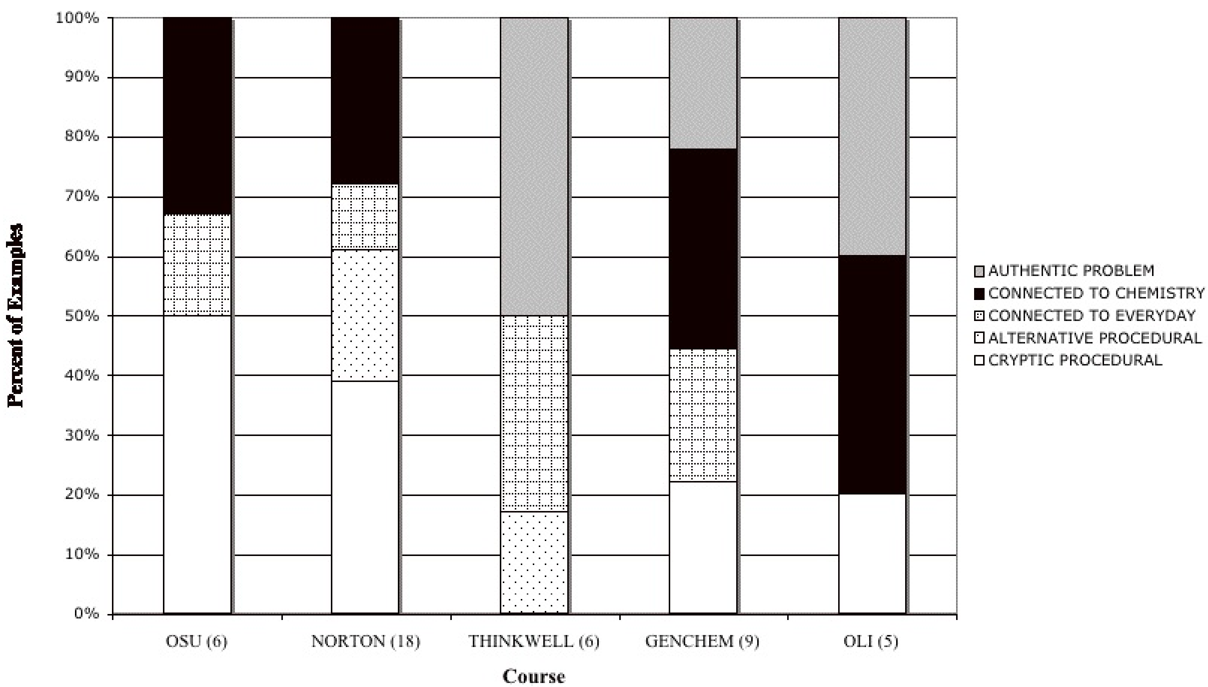


Figure 1. Distribution of example types by course. The numbers in parentheses are the total number of examples across the target topics of limiting reagents, molarity, and dilution for each course.

Except for OLI, each course has several examples coded as *connected to everyday* (COE). Although these examples are meant to serve as connections between the familiar and abstract chemical phenomena, often the courses do not unpack the analogical relationship. Recall the sample example coded as COE from the Methods section. In this example from THINKWELL, a surface comparison is made between a concentration unit (grams per ounce) representing a mass quantity per unit volume with a concentration unit (molarity) representing a number quantity (moles) per unit volume (liter). Such an instructional move actually may promote the formation of a misconception about the meaning of molarity in the mind of the learner. Grams and moles do not have an intuitive relationship. For example, one mole of table sugar (sucrose) dissolved in one liter of solution and one mole of grape sugar (glucose) dissolved in one liter of solution each produce a solution whose concentration is 1 M (one mole per liter). However, since the mass of a sucrose molecule is nearly twice the mass of a glucose molecule, the concentration of the sucrose solution reported as grams per ounce would be nearly twice that of the glucose solution reported in grams per ounce.

Figure 2 relates the mean number of examples per topic to the *complexity index*, the percentage of examples in the *connected to chemistry* and *authentic problem* categories. Although NORTON has the greatest mean number of examples per target topic (six), the majority of these examples are cognitively simple as indicated by the relatively low complexity index score (< 30). On the other hand, OLI ranks high on the complexity index (80) but the mean number of examples per topic is less than two. None of the courses examined here combined both the quantity and quality of examples that might be needed to promote learning. However, it is likely that improving courses by increasing the quantity of examples is easier than increasing the complexity of them. Furthermore, because OSU and NORTON are supplemental websites for traditional courses, users of these websites may be able to access examples of higher cognitive quality elsewhere (lectures, textbook, recitation sections). Since THINKWELL, GENCHEM, and OLI are stand-alone courses, they should incorporate more examples into their lessons.

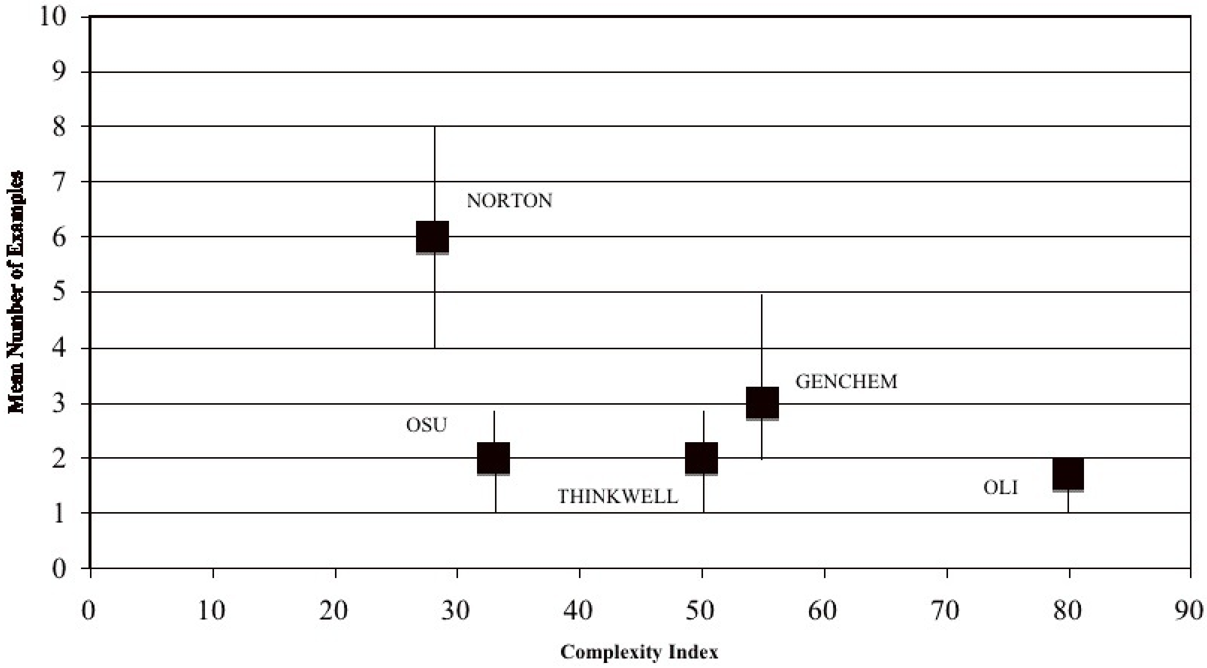


Figure 2. Mean number of examples and complexity index per target topic and course. Vertical lines mark the range of number of examples over the target topics (limiting reagents, molarity, dilution).

Tasks

Table 3 displays the number of tasks by target topic for each course. There is considerable variation in the format and content of these tasks. OSU and THINKWELL provide only multiple-choice tasks that immediately follow a topic's exposition. OSU's tasks are formatted as three-item quizzes randomly generated from a quiz bank. Each time a quiz on a target topic is selected by a given user, different items are presented. THINKWELL's tasks are formatted as a ten-question *exercise* that does not change each time the exercise is selected. NORTON provides multiple-choice tasks in quiz format at the end of each chapter. Each chapter has a bank of about 40 items. Students can select quizzes ranging in size from five to 40 or more items. NORTON also provides practice problems that, along with OLI and GENCHEM, are not in a quiz format. OLI and GENCHEM do not provide quizzes at all. As can be seen from Table 3, most of the courses provide at least six tasks per target topic. NORTON provides about nine although only two are devoted to dilution. GENCHEM and OLI provide supported tasks (tutorials[2]) that present new data each time the task is opened. However, these tutorials basically consist of procedural practice with either no, or an unchanging, cover story.

[2]Additional discussion of tutorials is included in the *Online Features* section

Table 3
Number of Tasks by Topic and Course

Topics	Course				
	OSU	NORTON	THINKWELL	GENCHEM	OLI
Limiting reactants	3	13	10	9	4
Molarity	9	12	5	6	7
Dilution	6	2	2	5	5
Total	18	27	17	20	16

Figure 3 shows the frequency of tasks in each level of cognitive demand for each course summed across the three topics (limiting reagents, molarity, dilution) analyzed. Cognitively simple tasks include those that require the recall (REC) of information from memory or the execution of a simple procedure (SPR). Cognitively complex tasks include those that require students to integrate two or more procedures (CPR), reason conceptually (CON) without algorithmic procedures, and solve problems that may not have a set solution path and are situated within the context of the laboratory or real life (AUT). All of the courses except OSU offer opportunities for practice at multiple levels of cognitive complexity. Nearly all of OSU's tasks emphasize the drill of simple procedures. Such computational rehearsal does serve to promote speed and accuracy. But without practice with complex problems in which these procedures are necessary but not sufficient for solution, the procedures may be quickly forgotten or learners may be unable to intuit their use in a new problem context. NORTON and OLI provide tasks in which students must combine two or more procedures. These activities can aid learners in interconnecting their chemistry knowledge framework, a move that promotes both fluency and flexibility. GENCHEM and OLI offer practice opportunities for simple procedures but also provide authentic tasks to which they can be applied. As with studying authentic examples, practice with authentic tasks promotes encoding opportunities (*hooks*) in the learners' cognitive framework thereby facilitating retention and future transfer.

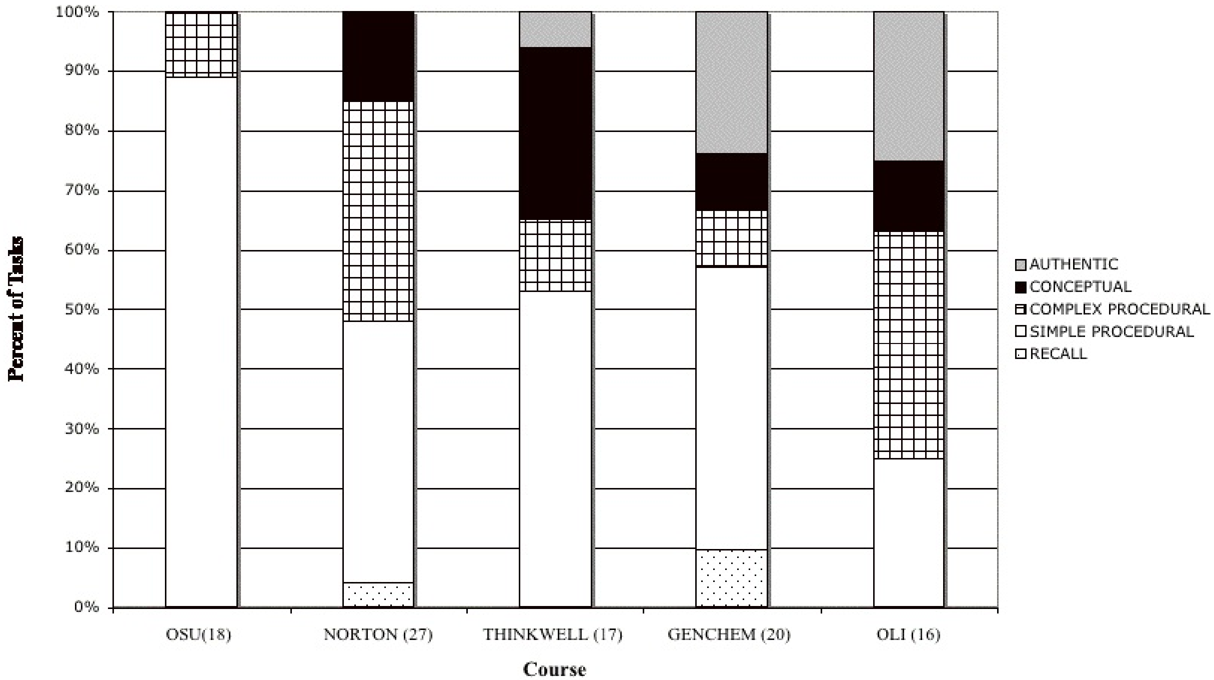


Figure 3. Distribution of task types by course. The numbers in parentheses are the total number of tasks across the target topics of limiting reagents, molarity, and dilution for each course.

Figure 4 relates the mean number of tasks per topic to the *complexity index*, the percentage of all tasks in the *complex procedural*, *conceptual,* and *authentic problem* categories. At one extreme is the OSU course that offers fairly simple tasks. At the other extreme is OLI that offers a preponderance of complex tasks. The remaining three courses are clustered around the 50% level of cognitive complexity but with NORTON having nearly 50% more practice opportunities than the other courses. However, NORTON does not provide any authentic practice so that students can experience *knowledge in use*.

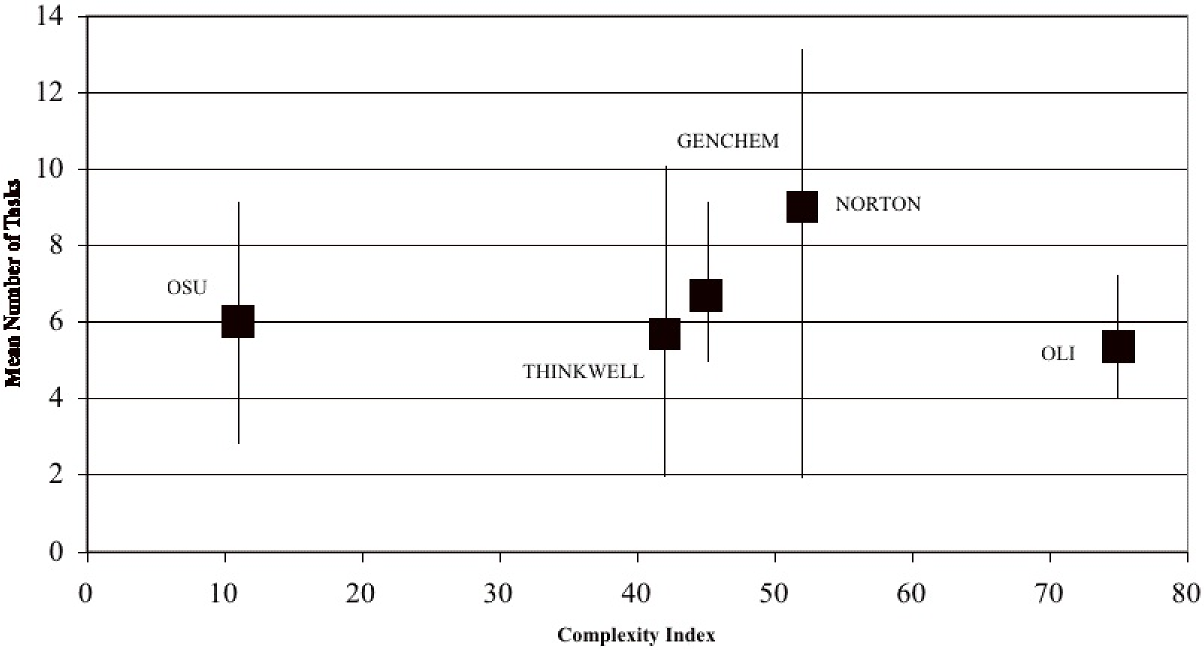


Figure 4. Mean number of tasks and complexity index per target topic and course. Vertical lines mark the range of number of tasks over the target topics (limiting reagents, molarity, dilution).

Online Features

Interactive Learning Objects

Unlike static textbooks, online courses can engage learners with interactive learning objects that range from providing quiz results to exploring virtual environments. Table 4 summarizes the types of interactive learning objects provided by each course. OSU provides only one type of dynamic learning object, specifically *assessments* in (the form of quizzes) with feedback, whereas GENCHEM offers a full range of interactive opportunities. NORTON, THINKWELL, and GENCHEM support students in complex problem solving by relieving them of hand *computations* through applets that automatically calculate quantities such as molar mass (molecular weight) from chemical formulas. These three courses also centralize needed atomic data within an interactive periodic table (*information retrieval*). NORTON, GENCHEM, and OLI offer *tutorial* objects that incorporate both feedback and coaching in the service of developing student proficiency with specific, albeit complex, procedures. Only GENCHEM and OLI provide *exploratory* environments in which students can freely change parameters and note the systemic changes. Coordination of these two activities may promote development of conceptual connections between two or more of the different levels of the domain's structure (i.e., macroscopic, submicroscopic, and symbolic). The use of feedback, tutorials, and exploratory environments will be described and discussed in greater detail in the following sections.

Table 4
Types of Interactive Learning Objects in Each Course

	Courses				
Interactive Objects	OSU	NORTON	THINKWELL	GENCHEM	OLI
Computational		x	x	x	
Information Retrieval		x	x	x	
Assessment	x	x	x	x	x
Tutorial		x		x	x
Exploratory				x	x

Feedback

Table 5 summarizes the feedback features of each course. OSU provides the least variety and degree of feedback--learner-controlled, confirmatory feedback for quizzes. NORTON and OLI place control with the learner or program depending upon the activity. NORTON’s quizzes and OLI’s exercises have feedback under program control. The feedback for both NORTON’s and OLI’s tutorials as well as OLI’s simulations is under learner control. The differentiation of the locus of control across these contexts correlates well with the function of the activity. OLI’s exercises and NORTON’s quizzes serve as knowledge assessments in which feedback encourages students to monitor their performance. On the other hand, tutorials and simulations serve as supports for knowledge acquisition by the learner who may not need automatic feedback in the form of confirmation or hints at every step in the process. Across all the courses other than OSU, informative feedback is predominantly in the form of hints. In addition to hints, GENCHEM and OLI also have partially adaptive feedback in their tutorials. This adaptive feedback is in the form of step-by-step directions that are automatically generated after one or two unsuccessful attempts at solution.

Table 5
Feedback Features of Each Course

	Courses				
Feedback Features	OSU	NORTON	THINKWELL	GENCHEM	OLI
Location					
Quizzes	x	x	x		
Exercises				x	x
Tutorials		x		x	x
Simulations				x	x

Control					
Program		x			x
Learner	x	x	x	x	x
Type					
Confirmatory[1]	x	x	x	x	x
Elaborative[2]		x	x	x	x
Informative[3]		x	x	x	x

[1]Feedback indicates whether response is correct or incorrect.
[2]Feedback explains correct solution and/or points out errors.
[3]Feedback gives hints, strategic clues, or adapts the activity based upon a learner's response.

Tutorials

NORTON, GENCHEM, and OLI all provide tutorials, or scaffolded practice, of stoichiometric procedures that have been explicated by text and/or videos. Each of the three courses provides support somewhat differently with regard to the specificity of hints and feedback. Figure 5 shows an example of general supported practice from NORTON where a simple procedural problem is presented for the learners to solve (see Figure 5A). After entering a response, the students may request feedback by clicking on the *check answer* box. If the answer is correct, confirmatory feedback is given with an option to choose elaborative feedback (*view solution*). If the entered answer is incorrect (see Figure 5B), a *review* option returns the student to the initial explication, which could be considered a hint or informative feedback, albeit opaque to the learner. Two other options include *try again* or *view solution* (elaborative feedback). This tutorial seems to assume that students will be able to induce the solution process through repeated reading of the initial explanation. On the other hand, the availability of the complete solution may result in students simply memorizing the steps to achieve the answer. Each time the student opens this tutorial, the same set of problems is presented, a situation that precludes the opportunity for practice with another set of variable values. The support provided by such a tutorial is minimal: confirmatory feedback, referral to the original explanation for review, and elaboration of the solution process. Similar tutorials are available for molarity, but not dilution, tasks.

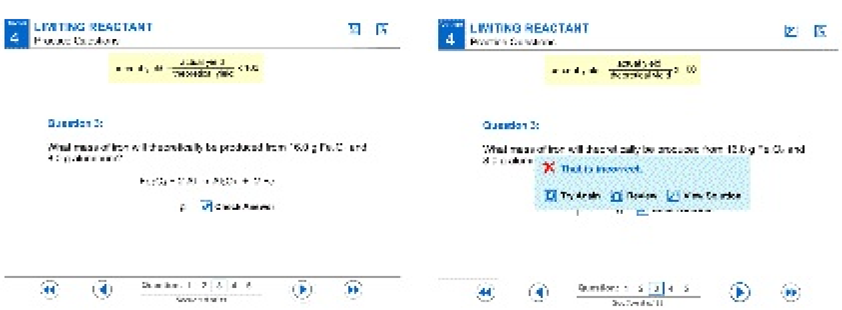
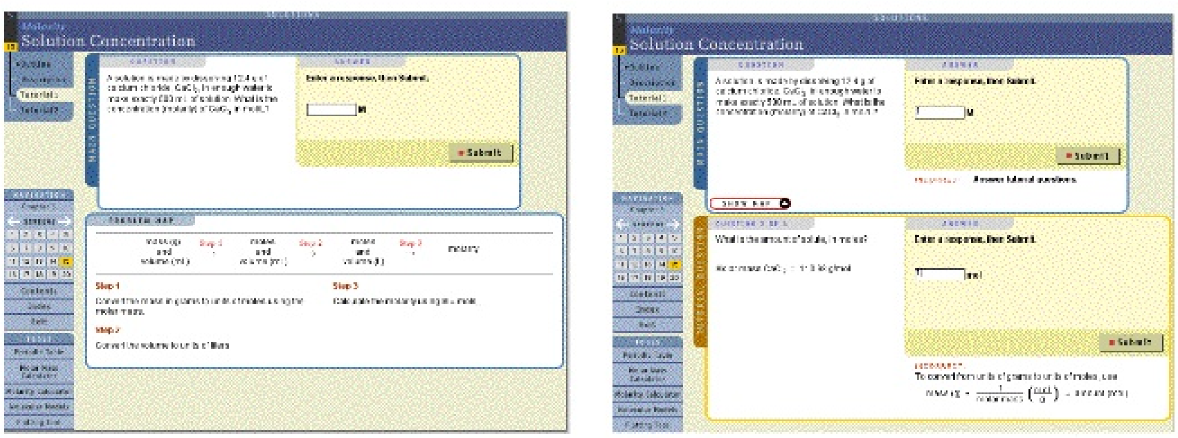


Figure 5. Excerpt of the Limiting Reactant tutorial from NORTON: A task as it appears to students (left) and the feedback options when an incorrect (or no) answer is entered and the *check answer* button is chosen (right).

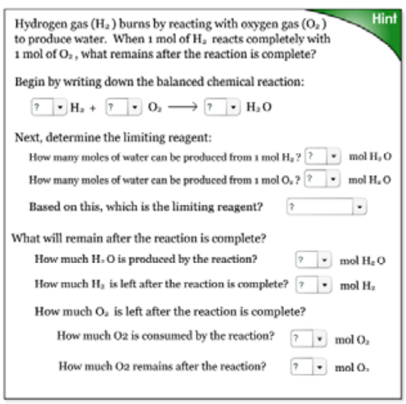
Figure 6 displays an example of a tutorial from GENCHEM. As with the NORTON tutorials, the task is of a simple procedural nature. However, the scaffolding provided by GENCHEM is more specific than that of NORTON. The task is accompanied by a *problem map* that decomposes the solution process into a series of subgoals (see Figure 6A). Students enter an answer by clicking on *submit*. A correct answer results in a confirmatory message. An incorrect answer results in a sequence of subtasks to guide students through the solution process. An incorrect response to a subtask results in elaborative feedback that includes a procedure for the subtask but not its correct answer (see Figure 6B). In order to proceed to the next subtask, the students must enter the correct answer. At no time are the correct answers to the original problem or to any of the subtasks provided (i.e., no bottom-out hint). Students may choose to retry the original problem at any time or to work out each subtask until arriving at the final solution. Extensive support is available in this tutorial but students can choose at anytime to use it or return to the original problem. The tutorial is parameterized so that each time it opens, new values for the variables are presented. Such parameterization provides some variation in practice opportunities similar to that found in different end-of-the chapter textbook problems. Students can continue to practice the procedure with different variable values until they are able to solve the specific problem type without any support. Tutorials are available for molarity and dilution, but not limiting reagents, tasks.



(A) (B)

Figure 6. Excerpt of the Molarity tutorial from GENCHEM. (A) shows a task as it first appears to students. (B) shows the feedback produced by entering an incorrect answer to a subgoal.

OLI provides two types of tutorials. One type (see Figure 7A) is similar to those from NORTON in that it is not parameterized. Like GENCHEM's tutorials, scaffolding includes a solution path with feedback. Unlike GENCHEM's tutorials, however, each subtask includes a bottom-out hint (i.e., the correct answer). A correct response turns green. This confirmation is accompanied by elaborated feedback that includes a brief explanation of why the response is correct. An incorrect response turns red and is accompanied by an error message. A series of hints can be invoked by clicking on the hint button at any time. The first hint reminds the learners of the goal of the particular problem. Succeeding hints give more detail on how to carry out a particular step. The last hint is a bottom-out hint, an explicit explanation of how to do that step. The second type of OLI tutorial (see Figure 7B) contextualizes the use of stoichiometry in a real-world problem, the elimination of arsenic from drinking water via a chemical reaction. This particular tutorial supplies encoding opportunities for learners in that the algebraic calculations of a limiting-reagents task are used in the service of solving a real-world problem. This OLI tutorial differs from those of NORTON and GENCHEM since it provides instantiations of *knowledge in use*. Unlike the previously described OLI tutorial, students may attempt the entire problem before viewing a step-by-step scaffolded procedure of subtasks that includes hints and feedback. After three incorrect attempts at solving the problem, however, students must reload a new problem before proceeding. At this point students may choose to make use of the scaffolding to guide the solution process. Once the scaffolding is initiated, learners may not attempt the original task on their own and must complete all of the subgoals provided by the tutorial. Such a restriction on the students' synthesis of a solution may actually promote rote learning of the procedure rather than its integration. Although OLI does not provide tutorials for molarity and dilution problems, individual tasks for these topics are accompanied by confirmatory feedback and hints.



(A)

(B) →

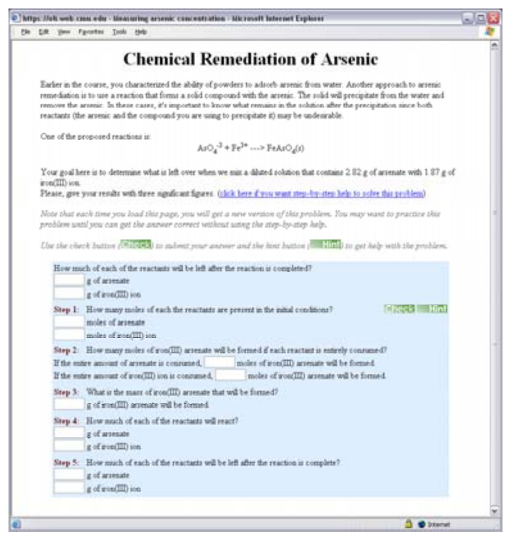


Figure 7. Two types of tutorials for limiting reagents from OLI. (A) decomposes a procedural task into subgoals for learners to solve. (B) provides a real world problem for which subgoals are provided upon request.

Tutorials across the three courses that offered them (NORTON, GENCHEM, OLI) are similar in that they all provide feedback in the form of hints and confirmations. The tasks are predominantly of a simple procedural nature that function as exercises of algebraic manipulations, albeit with vocabulary and variables rooted in chemistry. The one exception is the OLI tutorial whose design situates the algebraic manipulations of stoichiometry in the context of a real-world use for analytical chemistry. Such a tutorial may both promote proficiency with the algebraic procedures and foster conceptual understanding by encoding knowledge in use.

Exploratory Environments

GENCHEM and OLI are the only courses that provide simulations as dynamic learning objects (see Figure 8). Although the simulations are accompanied by goal-directed activities, the applets also provide environments for exploration. GENCHEM provides a graphical simulation of limiting reagents for multiple chemical reactions (see Figure 8A). Students select a reaction and an initial mass for one of the reactants. Additional increments (one or ten grams at a time) of another reactant can then be added. The graphical display shows the proportion of each substance (in grams) in the reaction mixture. This simulation may aid learners in realizing that the ratio of substances represented by the chemical equation is not equivalent to the ratio of grams of substances in the reaction mixture. (Recall that chemical species react with each other on a numerical basis but chemists measure these species by their mass.) By stripping away the paraphernalia of a lab bench, this simulation focuses the students' attention on the mathematical (proportionality) aspects of limiting reagents. OLI's simulation, the Virtual Lab (see Figure 8B), includes representations of the macroscopic tools of the lab bench (*workbench*) in addition to revealing the submicroscopic characteristics of the tools' contents in tabular as well as graphical form (*solution information panel*). The Virtual Lab is a simulated environment for authentic solution chemistry activities that employ the stoichiometric topics of molarity and dilution. Students can mix substances from the stockroom and observe the subsequent changes in concentration of the species involved. OLI provides real-world problems for students to solve using the Virtual Lab, such as determining whether the concentration of arsenic in a water sample exceeds the World Health Organization's recommendations or how much of a particular adsorbent will remove all of the arsenic in a water sample. By simulating an actual laboratory environment and posing real-world chemistry problems, OLI may provide multiple encoding opportunities for learners to develop an intuitive understanding of chemical processes. By making the invisible (submicroscopic species) visible (via the solution information panel), the Virtual Lab helps students form connections among the three levels of chemistry knowledge (macroscopic, submicroscopic, symbolic).

The GENCHEM and OLI simulations provide different types of interfaces and different levels of scaffolding for the learner. GENCHEM's interface can be considered *stripped down* since it highlights only those variables directly involved with the concept of limiting reagents. Such a design immediately focuses the learners' attention on the basic proportional relationships. GENCHEM then leads learners through a series of superimposed actions designed to point out these relationships within a given chemical reaction. A review of research studies that have evaluated learning from simulations shows that without instructional support gains are often unclear, disappointing, or both. Students who are unfamiliar with a domain benefit from sequenced assignments when first interacting with a simulation (Swaak & De Jong, in press). Unlike GENCHEM, the interface for OLI's Virtual Lab is modeled after an actual chemistry lab bench and includes simulated glassware, instrumentation, and solutions. Students are presented with an authentic problem to solve using the simulation. Scaffolding is provided through a series of hints that are available if the student requests. These hints are not procedural in nature but rather remind students of the goal of the activity and give some general advice on how to approach a solution. The explicit feedback provided to students' answers responds to both correctness and error type if appropriate. After three failed attempts at solving a problem with the simulation, the system gives the student the correct answer and then requires the student to reload the problem, which comes with new random parameters. Students are free to manipulate objects in the Virtual Lab in a goal-free manner as well. In this exploratory mode, feedback is implicit via the solution information panel of the Virtual Lab (see Figure 8B). Since the OLI course is a review of stoichiometry, the material is somewhat familiar to the users so a less-structured approach to working with the simulation is appropriate. In order to encourage exploration, OLI's developers may want to consider adding more substances to the stockroom (other than those present in the service of achieving the predefined specified goal).

(A)

(B)

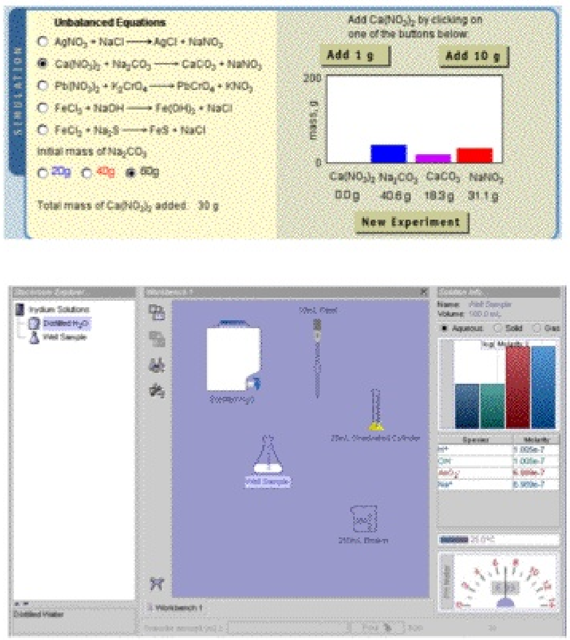


Figure 8. Screen shots of simulations from (A) GENCHEM and (B) OLI.

Summary

The proposed framework for examination and evaluation of online chemistry courses combines a descriptive taxonomy of online resources with a functional analysis of examples, tasks, and interactive features created to promote learners' active engagement with authentic inquiry in the discipline of chemistry. Results of the investigation show that the courses that were examined differ considerably along several dimensions (e.g., implementation of online resources, quantity and quality of examples and tasks, opportunities for authentic inquiry and exploration). Although OLI provides the highest degree of cognitive complexity among examples and tasks (>70%), its actual number of examples and tasks is the lowest among all the courses (less than two examples per topic and less than five tasks per topic on average). Each course provides some degree of immediate feedback. The level of feedback ranges from the simple confirmation of quiz responses (OSU) to the scaffolding of complex problem solving through specific and/or general hints (GENCHEM, OLI). NORTON, GENCHEM, and OLI provide interactive tutorials for supported practice of simple procedures. All three courses respond to student answers with confirmatory feedback. GENCHEM and OLI provide an additional level of informative feedback that may directly aid in student problem solving. They are the only courses that provide exploratory opportunities through simulated learning objects. GENCHEM's simulations impose an ordering of actions on the learner, accompanied by confirmatory and procedural feedback, within a basic symbolic interface. The simulated reality of OLI's Virtual Lab allows learner-imposed sequencing of actions that are scaffolded through generalized hints and goal reminders. Both types of simulations allow for exploratory actions by the student in addition to the courses' prescribed tasks. This wide variability in the level of cognitively-informed instructional strategies and implementation of interactive features suggests that with regard to online instruction, the goal of promoting the development of a fluid and flexible command of chemistry via active construction of knowledge frameworks and development of inquiry skills is not uniformly shared within this educational community.

Conclusions

The traditional goals of chemistry education were for students to assimilate and reproduce facts and procedures by means of explicit products, namely tests. Texts and courses were in essence a *rhetoric of conclusions* in which knowledge was conveyed through didactic instruction as a collection of irrevocable truths (Schwab, 1962). Such a body of definitional knowledge is often inert, unusable out of the context in which it was taught, namely within the carefully organized structure and content of classroom notes. The ability to both understand and work on complex or ill-defined problems, however, requires an intuitive knowledge base. This level of intellectual sophistication may best be developed through authentic inquiry in which tools such as stoichiometry are developed as needed in the planning and executing of experiments as well as the interpretation of data. But authentic activity in chemistry is often too dangerous, or too time consuming, or too obscured by the interaction of multiple variables to be of cognitive value to learners. Furthermore, without the practiced kinesthetic skills needed for laboratory work, the quality of data from which inferences are made is questionable. A decade ago Osin and Lesgold (1996) proposed that intelligent computer systems coupled with domain simulations might facilitate a cognitive apprenticeship model of learning by which novices (the students) would be supported by experts (in this case, the computer) as they solve authentic, albeit difficult, tasks in the process of developing competency in a domain.

In the early days of educational technology some viewed its development as sort of a *magic bullet* that would transform instruction, perhaps even replace teachers. Technology alone, however, is not sufficient for creating the type of instruction that supports the meaningful learning needed for complex problem solving within the chemistry laboratory or related to the socioeconomic decisions confronting a 21st-century way of life. Assuming that the World Wide Web can support such learning is unfounded since it was not designed to teach anything. Rather, it provides quick access to a vast repository of information--a virtual library. Technology, then, is a necessary but not sufficient condition for transforming learning environments. Technology provides the tools to create the interactions (e.g., simulations, feedback, tutorials, etc.) that can facilitate learners' construction of their knowledge frameworks. But it is the findings from learning science, whether facilitated by technology or not, that must guide the development of online courseware. For example, to learn from a simulation, the students must both understand what they should accomplish as well as be scaffolded and coached appropriately in achieving their goals. Such informed instructional design may serve to individualize online courseware in a way that optimizes learning among diverse groups of students.

Development of effective online courses will require a joint effort among experts in content, psychology, pedagogy, and instructional design--a distributed expertise. A review of chemistry online courses supports this assertion. GENCHEM and OLI are two courses that stand out as cognitively, pedagogically, and technologically informed, albeit with room for improvement. Both of these courses were developed by collaboration among experts in chemistry, learning sciences, and computer technology. The other courses, although content valid, appear to be lacking significant input to their designs from one or more of the other areas of expertise. THINKWELL consists of videotaped traditional lectures with colorful visuals and supplementary notes. Opportunities for interaction are limited to responding to quiz questions and navigating through the program. OSU is essentially a professor's lecture notes delivered online as text. There are no visualizations or interactions except the act of navigating throughout the website and responding to quiz questions. NORTON provides rudimentary tutorials with minimal scaffolding as well as multiple examples and tasks, the majority of which are cognitively simple in nature. Furthermore, each course other than OLI treats the topic of stoichiometry as an end to itself rather than *knowledge in use*. Such a bottom-up approach to chemistry in which the domain is decomposed into a multitude of skills to be mastered before getting to the *good stuff*, is characteristic of traditional chemistry instruction with its attendant problems for memorable learning (Evans et al., 2006). OLI situates stoichiometry instruction within the context of an analytical problem, the measurement and remediation of arsenic in groundwater. Perhaps it is through such instantiations of authentic inquiry facilitated by online technology that meaningful learning through the development of an intuitive knowledgebase--unencumbered by time, distance, intellectual, or socioeconomic constraints--can be realized.

APPENDIX B

SOLICITATION LETTER

DEAR "STUDENT":

Welcome to Carnegie Mellon University. As you look forward to your freshman year we wish you well in your academic endeavors. I am writing to tell you about an opportunity to participate in a study being conducted by my research group in the chemistry department that we anticipate will help you in your studies.

Many entering students register for Introductory Modern Chemistry I (CHEM105) during their freshman year. To ensure that all students who have registered for the course have a solid understanding of the same basic chemistry content, this course requires students to take and pass a test on basic chemistry content. The test is given during the first week of the course. Students who fail the test may retake the test up to five additional times during the course one their own time. A passing score is not part of the final grade but is a requirement for completing the course successfully.

The responsibility for learning the material traditionally has rested with the student alone. To better serve and support students our chemistry group has designed a special set of materials that can help you study for this required test. As instructional designers, we are interested in learning about the instructional efficacy of these materials. Should you choose to become a part of our research, the materials will be made available for your use online during several weeks in July and August. After using the materials to learn and study, you will be asked to complete two tests. The first test will be completed by you before arriving on campus. The second test will be administered in a classroom setting at a specified time during Orientation Week.

The faculty responsible for Introductory Modern Chemistry I (CHEM105) have agreed to waive the normal test requirement for this material for the course for those students who participate and pass the test. In addition, those students who complete the study will receive: \$10 upon completion of the self-study materials, \$10 upon completion of the first test delivered online, and \$30 upon completion of the second test during Orientation Week.

We are able to accept only the first 200 students that respond to this opportunity. Therefore, if you would like to be part of this research study, please email me as soon as possible at **chemstudy@cmu.edu**. Your participation is completely voluntary.

If you have any questions regarding this research study, please email me at **chemstudy@cmu.edu**.

Thank you for considering this opportunity that we believe will help you with CHEM105's requirements.

Sincerely,
David Yaron, Ph.D.

APPENDIX C

BACKGROUND SURVEY

NAME ____

(LAST) (FIRST) (MIDDLE INITIAL)

Thank you for answering the following questions about your high school educational experiences.

Science Coursework: Please check all that apply.

	High School	Advanced Placement	International Baccalaureate	Other (Please explain)
CHEMISTRY	______	_______	________	_________________________
BIOLOGY	______	_______	________	_________________________
PHYSICS	______	_______	________	_________________________
COMPUTER SCIENCE	______	_______	________	_________________________

Math Coursework: **Please check all that apply.**

PRE-CALCULUS	______	AP CALCULUS (AB)	______
CALCULUS	______	AP CALCULUS (BC)	______

Exams: Please report your scores for any of the following exams you may have taken.

	SAT II	Advanced Placement	International Baccalaureate	Other (Please explain)
CHEMISTRY	______	_______	________	_________________________

BIOLOGY	______	______	______	______________________
PHYSICS	______	______	______	______________________
COMPUTER SCIENCE	______	______	______	______________________
MATHEMATICS	______	______	______	______________________

SAT I SCORES:	MATH	______	VERBAL	______
ACT SCORES:	MATH	______	COMPOSITE	______

APPENDIX D

INFORMED CONSENT

Study Title: The Assessment and Evaluation of Online Study Materials for Introductory Chemistry

PRINCIPAL INVESTIGATOR: David Yaron, Ph.D.

The purpose of this study is to evaluate online learning materials for introductory chemistry. To ascertain the effectiveness of these materials we will assess student learning. As a participant in this study, you will be asked to complete a background survey about your previous educational experience and a series of chemistry lessons online. As soon as you have completed the lessons, you will be asked to take an online test about the material in the lessons. You will be asked to take a second test on the content in a classroom setting on the Carnegie Mellon University campus during Orientation Week.

There are no foreseeable risks or discomforts associated with this study. As a participant you may benefit from learning a challenging subject matter from carefully designed instructional environments. Attainment of a passing score on the second test will exempt you from the required mastery test on the content materials in CHEM105.

There will be no cost to you if you participate in this study.

Your participation is voluntary. Refusal to participate or withdrawal of your consent or discontinued participation in the study will not result in any penalty or loss of benefits or rights to which you might otherwise be entitled.

You will receive up to $50 for participating in this study: $10 upon completion of the background information survey and self-study materials, $10 upon completion (before Orientation Week) of the online test, and $30 upon completion of a second test during Orientation Week. This is for your time and personal cost of participation.

Your anonymity will be maintained during data analysis and publication/ presentation of results by any or all of the following means: (1) You will be assigned a number and names will not be recorded. (2) The researchers will save the data file records by number, <u>not</u> by name. (3) Only members of the research group will view collected data in detail. (4) Any files will be stored in a secured location accessed only by authorized researchers.

If you have any questions about this Study, you should feel free to ask them now or anytime throughout the Study by contacting:

Professor David Yaron
Department of Chemistry
4400 Fifth Avenue
Pittsburgh, PA 15213
(412) 268-1351
Email: yaron@cmu.edu

If you have any questions pertaining to your rights as a research participant; or to report objections to this Study, you should contact:

IRB Chair
Regulatory Compliance Administration
Carnegie Mellon University
5000 Forbes Avenue
Warner Hall, 4th Floor
Pittsburgh, PA 15213
Email: irb-review@andrew.cmu.edu
(412) 268-1901 or (412) 268-4727

The Carnegie Mellon University Institutional Review Board (IRB) has approved the use of human participants for this Study.

This Study is funded by the National Science Foundation and the William and Flora Hewlett Foundation, which are supporting the costs of this research. Neither Carnegie Mellon University (CMU), nor David Yaron will receive any financial benefit based on the results of the Study.

I understand the nature of this Study and agree to participate. I received a signed copy of my consent. I give the Principal Investigator, and his associates, permission to present this work in written and/or oral form for teaching or presentations to advance the knowledge of science and/or academia, without further permission from me provided that my image or identity is not disclosed.

____ ____________________
PARTICIPANT SIGNATURE DATE

____
PARTICIPANT NAME (please print)

APPENDIX E

SAMPLE EMAIL COMMUNICATIONS WITH PARTICIPANTS

1. Response to students interested in participating in study:

   Thank you for your interest in our chemistry research study. Please go to http://www.andrew.cmu.edu/org/chemstudy in order to read the informed consent document and the background survey. Directions for completing and sending us these forms also will be found at the website. Once we have received the documents, we will send you the directions for accessing the course materials. If you have any questions, you may email us at chemstudy@cmu.edu and we will get back to you within 24 hours.

2. Technology-rich treatment assignment:

   Thank you for agreeing to participate in our research study. We hope that your experience will be both enjoyable and helpful as you review some important chemical concepts and procedures.

   To get started, please download and read the attached PDF file which contains directions for accessing the study materials.

   Because you are part of a controlled research study, please do not share the course website or its contents with anyone. You are free to consult appropriate additional references, if needed, but the study materials have been developed to be self-contained. If you have any questions, please contact us at chemstudy@cmu.edu and we will get back to you within 24 hours. It should be noted that dial up internet connections will not be sufficient for the activities in this course.

   Again, thank you for agreeing to participate in this study and good luck!

3. Text-only treatment assignment:

   Thank you for agreeing to participate in our research study. We hope that your experience will be both enjoyable and helpful as you review some important chemical concepts and procedures.

   To get started, please go to http://www.andrew.cmu.edu/org/chemstudy/cc.html

   Because this is a controlled study, please do not share this website or its contents with anyone. You are free to consult appropriate additional references, if needed, but the materials have been developed to be self-contained. If you have any questions, please contact us at chemstudy@cmu.edu and we will get back to you within 24 hours.

Again, thank you for agreeing to participate in this study and good luck!

4. Request for participant progress update:

Thank you for participating in our chemistry study. We hope your experience so far has been both informative and enjoyable as you review stoichiometry concepts and operations.

We would like to know (1) which sections of the course you have completed by Thursday, August 4, and, (2) how much time you estimate that you have spent working on these materials. Please email this information to chemstudy@cmu.edu.

The first test will be available online from August 11-18. Please give yourself sufficient time for review and practice before requesting this test. When you are ready, email us at chemstudy@cmu.edu and we will send the directions for accessing the test. You will need about two hours of uninterrupted time to complete the test.

Thank you for your continued interest and hard work.

5. Announcement of online posttest availability:

Thank you for working so hard on the stoichiometry study materials. The online testing period begins today, August 11, and will continue through August 18. When you have completed the study materials, please take some time to review and practice with them before requesting the online test. Once you have received the test, please do not refer back to the materials until you have completed and returned the test to us.

When you send us a request for the test, please give us a time estimate, in total, that you have spent working with the materials. Then we will email the test to you as a PDF attachment. Please open the document and read the first page of directions carefully before downloading test. It is important to our research that you treat this test as one you would take in a classroom setting. You may use a calculator but no other resource materials. Please allow yourself a quiet, uninterrupted two-hour time period for taking the test.

We will grade these tests as "pass" or "fail" according to the criteria set for mastery by the chemistry faculty. You will be informed of your performance on the online test before the classroom test given during Orientation Week.

Thank you again for your continued participation in our research.

6. Announcement of campus posttest date and time:

In a few short days Orientation Week begins. We wish for you all the best as you begin your university career at Carnegie Mellon.

The last part of the chemistry study, the campus test, has been scheduled for Tuesday, August 23. The test will take place in Doherty Hall, Room 2315. Please arrive anytime between 2 PM and 3 PM. You may have up to 1.5 hours to complete the test in this classroom setting. Following the test you will be reimbursed for your contribution to our research efforts according to the schedule outlined in the invitation to join the study.

We are looking forward to meeting you next Tuesday on campus.

7. Sample response to a technology-rich treatment group participant who reported an error in the course. Relevant details were posted on Blackboard for other participants in this treatment.

Thank you so much for your comments. Please send us any other errors you may find.

You are completely correct regarding the hint box for the problem in "stoichiometric proportions of reactants." Furthermore, if you carry all the significant figures through the entire calculation and round at the very end, then the correct answer would be 0.658 g!

For the problem about $Ca_3(PO_4)_2$*: This problem reminds us that the significant figure "rules" are really only guidelines for considering the error in measurements, and when there is a question, one should always report on the "conservative" side. Let me explain:*

The atomic weight of Ca has 5 sigfigs (40.078). When multiplying by 3, stay at 5 sig figs (120.23) because of the multiplication rule for determining sigfigs. Now the total value for calcium mass has only 2 decimal places and is the fewest number of all the elements' masses so when adding the contributions of each element to determine the total molar mass, rounding is done to reflect the least number of decimal places (2).

Another view would be of not rounding any values until the end of the calculation. Therefore the contribution of calcium would be 120.234 g. When adding the masses of all the elements, the adding rule for sigfigs says to round to the fewest number of decimal places (3) so the final answer for the molecular weight of $Ca_3(PO_4)_2$ *would have 3 decimal places reported.*
Now, since we are going with the more conservative value, the course reports a molecular weight with 2 decimal places.

I hope this explanation helps. Thank you again for your careful attention to the course details. We appreciate your diligence! It will help us improve the next version.

8. Sample response to a participant from the text-only treatment group who reported an error in the study materials. When the error was corrected, revised materials with an explanation were sent to all participants in this treatment group via email.

I do apologize for the error and a quite serious one at that. I will have it corrected and reposted. The correct MW of AsO_2^- *is 106.9204 g/mol.*

Please work through the problem using this MW which, of course, will change the initial moles of AsO_2^- *to 0.01131683 mol. I am sending you a PDF of the revised calculation for you to check against your own!*

APPENDIX F

POSTTEST-1

DIRECTIONS: Please read all of these directions before beginning the test.

1. Make two copies of this test.

2. Print your name and CMU e-mail on each page.

3. On the first copy of the test, complete all the problems that you are able in one hour. We would prefer that you work from beginning to end. You may skip a problem and return to it within the 1-hour time frame.

4. When 1 hour has elapsed, continue your work on the second copy of the test. You may work as long as you wish up to one additional hour. Do not transfer what you completed on the first copy to the second copy of the test. Please write at the top of the second copy of the test how long you spent on the second copy of the test. If you do not need any time past the first hour, simply write the time you spent in total on the first copy of the test.

5. Show all your work for each problem. Please report solutions using the appropriate number of significant figures.

6. Treat this test as any other test you would take. Do not consult notes or other sources for help. You may use a calculator. Work uninterrupted for the entire test.

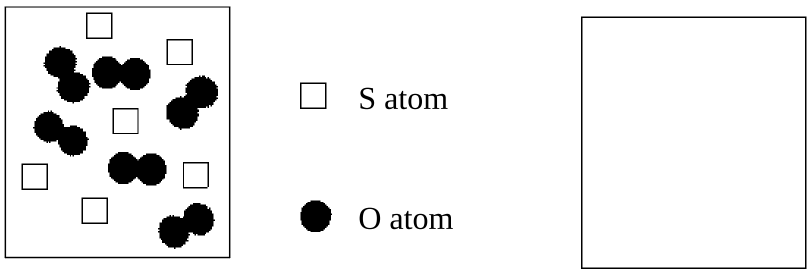
Thank you for your continued interest and support. Good luck!

David Yaron

1. Laughing gas, N_2O, is a weak anesthetic that has been used in dentistry since the late 18^{th} century. The formula, N_2O, means that in a sample of laughing gas (circle all that apply):
   (A) For every 100 atoms of oxygen (O), there are 200 atoms of nitrogen (N)
   (B) For every atom of nitrogen, there are 2 atoms of oxygen
   (C) For every 2 grams of nitrogen, there is 1 gram of oxygen
   (D) The compound is 36% oxygen by mass
   (E) The compound is 64% nitrogen by mass

2. A 10.00-g sample of ore contains 3.76×10^{22} atoms of molybdenum (Mo). The molecular weight of the ore is 160.07 g/mol. What is the percent by mass of molybdenum in the sample?

3. Figure (A) represents a mixture of S atoms and O_2 molecules in a closed container.



(A) (B)

Assuming the reaction goes to completion ($2\ S + 3\ O_2 \rightarrow 2\ SO_3$), draw what the product mixture looks like in Figure (B).

4. How many grams of LiCl are needed to make 2.00 L of a 0.250 M solution?

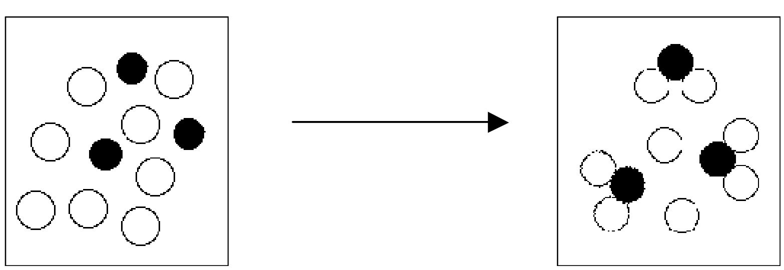
5. Three moles of carbon (C) are mixed with eight moles of sulfur (S) and after reacting the reaction mixture contains three moles of carbon disulfide (CS_2) and two moles of sulfur. Write a balanced equation for this reaction.

6. The molecular weight (molar mass) of Compound X is three times the molecular weight of Compound Y. What mass of X will have the same number of molecules as 21 g of Y?

7. A 25.0-mL sample of an acetic acid ($C_2H_4O_2$) solution (vinegar) is titrated with a 0.500 M NaOH solution. If 30.0 mL of the NaOH solution are required to reach the endpoint of the titration, how many grams of acetic acid ($C_2H_4O_2$) did the vinegar sample contain? Remember to show all your work.

$$C_2H_4O_2 + NaOH \Leftarrow NaC_2H_3O_2 + H_2O$$

8. The reaction of Element X (λ) with Element Y (○) is represented below.



Write the equation that describes this reaction:

9. For each of the following solutions' manipulations, please show all your work:

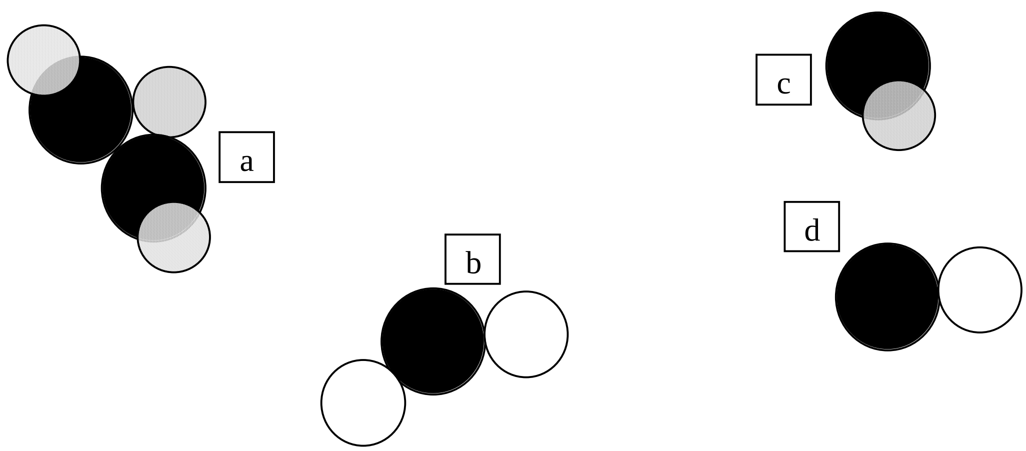
   (A) When 55.0 mL of a 0.25 M solution of maltose is diluted by adding 125.0 mL of water, what is the molarity of maltose in the final solution?

   (B) If 257 mL of a 0.75 M solution of maltose is reduced by evaporation to 195 mL, what is the molarity of the new solution?

   (C) If you combine 132 mL of a 0.85 M solution of maltose with 457 mL of a 0.24 M solution of maltose, what is the volume and molarity of the final solution?

10. When you mix 0.945 g of Sn and 1.834 g of I_2 in an appropriate solvent, 1.935 g of SnI_4, an orange solid, is formed. What are the theoretical and percent yields of SnI_4? Please show all your work.

11. Given that the white element weighs twice as much as the striped one, rank (from greatest to least) the percentage compositions of the black element in the molecules below. Please show all your work.



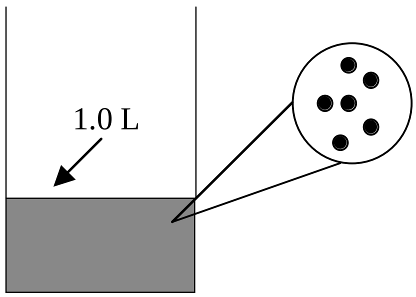
12. Assume that the reaction of rubidium (Rb) with these three acids takes place as shown and goes to completion.

   (A) $2\ Rb + 2\ H_2O \Leftarrow 2\ RbOH + H_2$
   (B) $2\ Rb + H_2C_2O_4 \Leftarrow Rb_2C_2O_4 + H_2$
   (C) $6\ Rb + 2\ H_3AsO_4 \Leftarrow 2\ Rb_3AsO_4 + 3\ H_2$

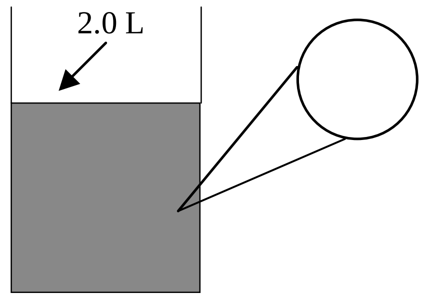
   If an equal mass of rubidium (Rb) reacts with each acid, compare the yields of hydrogen (H_2) produced in each reaction.

13. A 2.000 g sample of a Ni-Tl-Zn (nickel-thallium-zinc) alloy is dissolved in nitric acid. After the addition of excess HI (hydroiodic acid) to this solution, 1.750 g of TlI (thallium iodide), the only solid produced, is separated from the solution. Calculate the percentage of Tl (thallium) in the alloy. Please show all your work.

14. **Solution S** represents a 1.0 L sugar solution. The dots in the magnification circle represent the sugar molecules. To simplify the diagram, the water molecules are not shown.



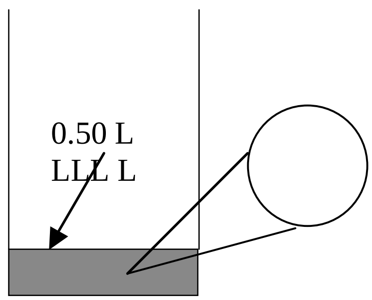
Solution S



Solution X

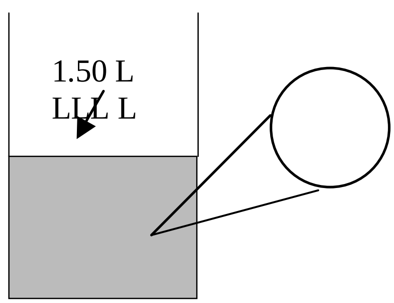
(A) **Solution X** results from adding 1.0 L of water to **Solution S**. Draw the view of sugar molecules in the magnification circle for **Solution X**.

(B) A fresh 1.0-L batch of **Solution S** is evaporated until only 0.50 L remains (**Solution Y**). Draw the view of sugar molecules in the magnification circle for **Solution Y**.



Solution Y

(C) **Solution Z** was created by mixing **Solution Y** (0.50 L) with a fresh batch of **Solution S** (1.0 L). Draw the view of sugar molecules in the magnification circle for **Solution Z**.



Solution Z

15. What is the empirical formula of citric acid, a sample of which contains 37.51% C, 4.20% H, and 58.29% O? Please show all your work.

16. A 6.80-g coin was dissolved in nitric acid. Excess NaCl was added and 6.21 g of solid AgCl was produced. Calculate the mass percentage of silver in the coin. Remember to show all your work.

$$Ag^{+}(aq) + Cl^{-}(aq) \Leftarrow AgCl(s)$$

Additional Information

Element	Atomic Weight (grams/mole)
Ag	107.8682
As	74.92160
C	12.0107
Cl	35.453
H	1.00794
I	126.90447
Li	6.941
Mo	95.94
N	14.0067
Na	22.989770
Ni	58.6934
O	15.9994
Rb	85.4678
S	32.065
Sn	118.71
Tl	204.3833
Zn	65.39

Compound	Molecular Weight (grams/mole)
$C_2H_4O_2$	60.0520
CS_2	76.141
fructose	180.1559
H_2O	18.0153
H_3AsO_4	141.9430
$H_2C_2O_4$	90.0349
HI	127.91241
$NaC_2H_3O_2$	82.0338
NaCl	58.443
NaOH	39.9971
N_2O	44.0128
Rb_3AsO_4	395.3226
$Rb_2\ C_2O_4$	258.9546
RbOH	102.4751
SnI_4	626.33
SO_3	80.063
TlI	331.2878

Avogadro's number = 6.02×10^{23}

1000 milligrams = 1 gram

1000 milliliters = 1 liter

1000 millimeters = 1 meter

APPENDIX G

POSTTEST-2

DIRECTIONS: Please read all of these directions before beginning the test.

1. Print your name and CMU email on both sides of each page.

2. For each question or problem, show all your work. Please report your answers in the appropriate number of significant figures.

3. You may use a calculator. Any additional information you may need is on the back of this page.

4. You have up to 1.5 hours to complete test. There is no need to rush.

5. When you have completed the test, please bring it to one of the proctors. You will then be remunerated and asked to sign a receipt list.

6. Thank you for all of your hard work on behalf of this chemical education research study.

1. An amino acid has a molecular weight (molar mass) of 776.9 grams/mole and contains 65.34% iodine by mass. What is the number of iodine atoms per molecule of this amino acid?

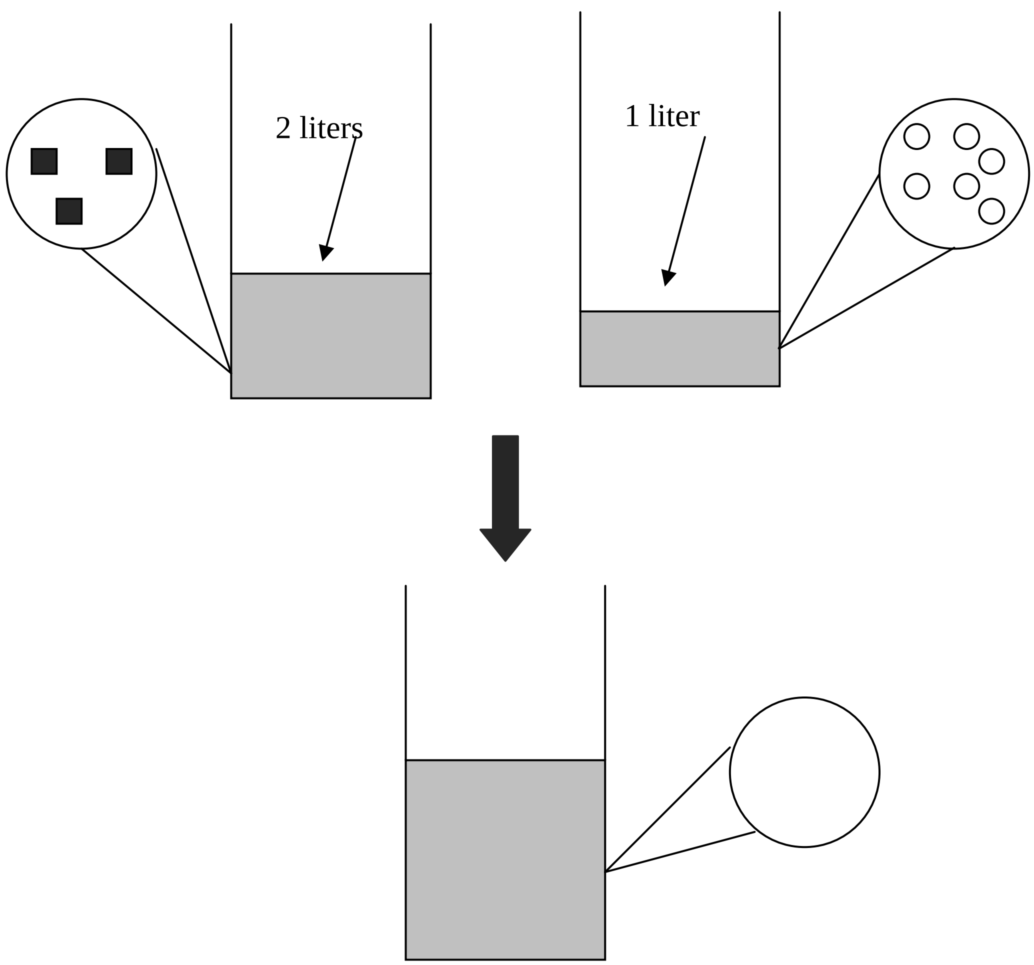
2. What is the molarity of a 15.0 mL solution that contains 89.3 milligrams KBr?

3. A 25.0-milliliter sample of HNO_3 was titrated with standard 0.100 M NaOH solution. The endpoint was reached after 20.0 milliliters of the NaOH solution was added. How many grams of HNO_3 did the sample contain?

$$HNO_3 + NaOH \rightarrow NaNO_3 + H_2O$$

4. What masses of what substances remain after 54 grams of aluminum (Al) and 32 grams of oxygen (O_2) react to produce aluminum oxide (Al_2O_3) as the only product? Remember to show all of your work.

5. The contents of the two beakers below are poured into a third beaker. Draw the view of molecules in the magnification circle provided for the third beaker.



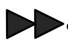
6. A 6.16-gram sample of CCl_4 reacted with excess oxygen to form 3.4 grams of $COCl_2$ as the only carbon-containing compound. What was the percent yield of that product? Please show all your work.

7. The formula for methane is CH_4. This means that, in methane, (circle all that apply)
   - A. for every 100 atoms of hydrogen there are 400 atoms of carbon
   - B. for every atom of carbon there are 4 atoms of hydrogen
   - C. for every gram of hydrogen there are 12 grams carbon
   - D. the compound is 25% hydrogen by mass
   - E. the compound is 80% hydrogen by ma

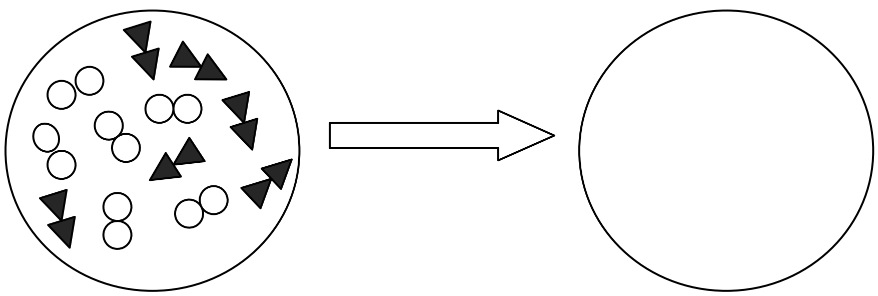
8. Assume the reaction of magnesium (Mg) with these three acids takes place as shown and goes to completion.
   - (1) $Mg + 2HCl \rightarrow MgCl_2 + H_2$
   - (2) $Mg + H_2SO_4 \rightarrow MgSO_4 + H_2$
   - (3) $3Mg + 2H_3PO_4 \rightarrow Mg_3(PO_4)_2 + 3\ H_2$

   If an equal mass of magnesium reacts with each acid, compare the yields of hydrogen produced in each reaction.

9. The atomic weight of element A is twice the atomic weight of element B. What mass of B will have the same number of atoms as 32 grams of A? Please explain your answer.

10. Chlorine (Cl_2)  and iodine (I_2)  react to give ICl_3. (**X**) is a mixture of chlorine and iodine.

    (A) Draw the resultant substance(s) in (**Y**) after the reaction goes to completion.



(**X**) (**Y**)

    (B) Write the balanced equation that describes this reaction:

11. A compound of sodium, sulfur, and oxygen contains 29.08% Na, 40.56% S, and 30.46% O. What is the correct empirical formula consistent with the precision of the data? Remember to show all your work.

12. The contents (A, B, and C) of three different bottles of fructose solutions were combined in a 1000-mL volumetric flask. The flask was then filled to capacity with distilled water. Solution A was 74 mL of 0.527 M fructose, solution B was 632 mL of 0.872 M fructose, and solution C was 139 mL of 1.16 M fructose. What was the final concentration of fructose in the volumetric flask? Please show all your work.

13. A sample that contains only $SrCO_3$ and $BaCO_3$ weighs 0.800 g. When it is dissolved in excess acid, 0.211 g of carbon dioxide (CO_2) is liberated by the acid. What percentage of $SrCO_3$ did the sample contain by mass? Assume that all carbon in the original mixture is converted to carbon dioxide. Remember to show all of your work.

14. A 2.00 g mixture of NaCl and $NaNO_3$ dissolved in water required 90.0 milliliters of 0.100 M $AgNO_3$ to react with all the chloride to form AgCl. What is the mass percentage of NaCl in the original sample? Please show all your work.

$$Ag^{+}(aq) + Cl^{-}(aq) \Leftarrow AgCl(s)$$

Additional Information

Element	Atomic Weight (grams/mole)
Ag	107.8682
Al	26.981538
Ba	137.327
Br	79.904
C	12.0107
Cl	35.453
H	1.00794
I	126.90447
K	39.0983
Mg	24.3050
N	14.0067
Na	22.989770
O	15.9994
P	30.973761
S	32.065
Sr	87.62

Compound	Molecular Weight (grams/mole)
$AgNO_3$	169.8731
$BaCO_3$	197.336
CCl_4	153.823
CO_2	44.0095
$COCl_2$	98.916
fructose	180.1559
HNO_3	63.0128
H_2O	18.0153
H_3PO_4	97.9952
H_2SO_4	98.078
methane	16.0425
$MgCl_2$	95.211
$Mg_3(PO_4)_2$	262.8577
$MgSO_4$	120.368
NaOH	39.9971
$NaNO_3$	84.9947
$SrCO_3$	147.63

Avogadro's number = 6.02×10^{23}

1000 milligrams = 1 gram

1000 milliliters = 1 liter

1000 millimeters = 1 meter

APPENDIX H

POSTTEST-3

General Chemistry 09-105 last term? (please circle): YES NO

Answer each of the questions to the best of your ability. Don't worry if you don't know the complete answers. Write whatever you can about each question. Remember: This is only an ungraded survey of your prior knowledge of chemistry.

1. The molecular weight (molar mass) of Compound A is four times the molecular weight of compound B. What mass of B will have the same number of molecules as 20 grams of A? Please show your work and explain your answer.

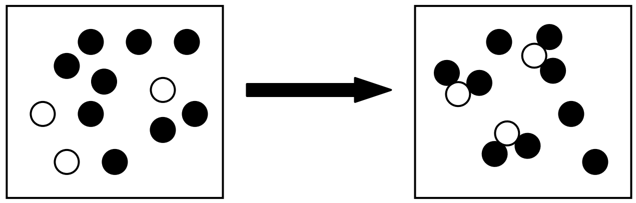
2. The mass of a sulfur atom is twice that of an oxygen atom. The formula, SO_2, means that in a sample of sulfur dioxide (circle all that apply):

   (A) The compound is 33% sulfur by mass.
   (B) For every 100 atoms of sulfur, there are 200 atoms of oxygen.
   (C) The compound is 50% oxygen by mass.
   (D) For every 2 grams of oxygen, there is 1 gram of sulfur.
   (E) For every atom of oxygen, there are two atoms of sulfur.

3. The mass of a mole of molybdenum (Mo) atoms is eight times that of a mole of oxygen (O) atoms. Arrange the following oxides of molybdenum in order from least to greatest percentage by mass of molybdenum. Please show all your work.

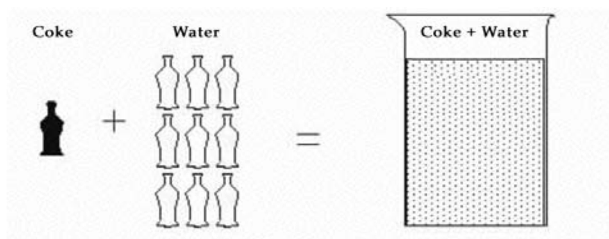
   MoO_2
   MoO_3
   Mo_2O_3
   Mo_2O_5

4. The reaction of Element W (○) with Element D (λ) is represented below.



Write the balanced equation that describes this reaction.

5. You are mixing the contents of a bottle of Coke with the contents of nine bottles of water of equal volume. The concentration of sucrose in the Coke is 1 M. What is the final concentration of sucrose in the beaker? Explain how you determined your answer.

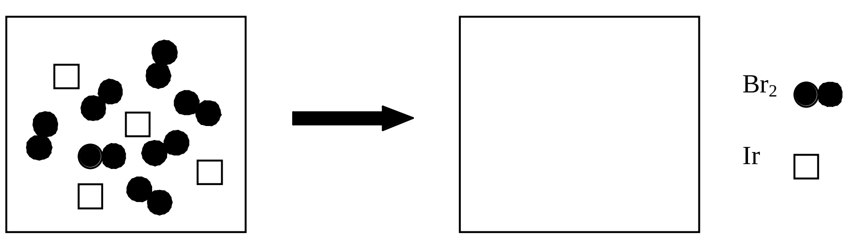


6. Calcium carbonate (chalk, limestone) reacts with acid to form a calcium salt, carbon dioxide, and water. Assume that the reaction of calcium carbonate with these three acids takes place as shown and goes to completion.

(A) $CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$
(B) $CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + CO_2 + H_2O$
(C) $3CaCO_3 + 2H_3PO_4 \rightarrow Ca_3(PO_4)_2 + 3CO_2 + 3H_2O$

If an equal mass of calcium carbonate ($CaCO_3$) reacts with excess amounts each acid, compare the yields of carbon dioxide (CO_2) produced by each reaction.

7. Figure (A) represents a mixture of iridium atoms and bromine molecules in a closed container. Assuming the reaction goes to completion ($2Ir + 3Br_2 \rightarrow 2IrBr_3$), draw what the mixture looks like in Figure (B) after reacting.



(A) (B)

8. Hydrochloric acid and potassium hydroxide react to form potassium chloride and water:

$$HCl + KOH \rightarrow KCl + H_2O$$

If the molarity of an HCl solution is twice the concentration of a KOH solution, compare the volumes of each solution needed to react completely. Please show all your work.

9. Magnesium nitrate and potassium hydroxide react to form magnesium hydroxide and potassium nitrate according to the following chemical equation:

$$Mg(NO_3)_2 + 2KOH \rightarrow Mg(OH)_2 + 2KNO_3$$

Assuming the reaction goes to completion, determine the number of moles of each substance remaining when 2 moles of magnesium nitrate and 2 moles of potassium hydroxide are mixed in a closed reaction vessel. Please show all your work.

10. Two different non-reacting sugar solutions are mixed: 100 mL of 1.0 M glucose and 400 mL of 0.1 M fructose. What is the molarity of each sugar in the final solution? Please show all your work.

APPENDIX I

POSTTEST-1 SCORING KEY

POSTTEST-1 SCORING KEY

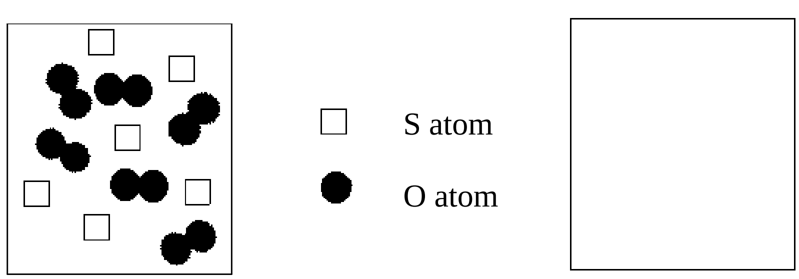
1. Laughing gas, N_2O, is a weak anesthetic that has been used in dentistry since the late 18th century. The formula, N_2O, means that in a sample of laughing gas (circle all that apply):
   (A) For every 100 atoms of oxygen (O), there are 200 atoms of nitrogen (N)
   (B) For every atom of nitrogen, there are 2 atoms of oxygen
   (C) For every 2 grams of nitrogen, there is 1 gram of oxygen
   (D) The compound is 36% oxygen by mass
   (E) The compound is 64% nitrogen by mass

   SCORING: 1 pt. each for (A), (D), (E). 5 pts. for all; no credit for any other response

2. A 10.00-g sample of ore contains 3.76×10^{22} atoms of molybdenum (Mo). The molecular weight of the ore is 160.07 g/mol. What is the percent by mass of molybdenum in the sample?

   SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

3. Figure (A) represents a mixture of S atoms and O_2 molecules in a closed container.



   Assuming the reaction goes to completion ($2\ S + 3\ O_2 \rightarrow 2\ SO_3$), draw what the product mixture looks like in Figure (B).

SCORING: 1 pt. for each substance's correct amount; 5 pts. if all substance amounts correct

4. How many grams of LiCl are needed to make 2.00 L of a 0.250 M solution?

   SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

5. Three moles of carbon (C) are mixed with eight moles of sulfur (S) and after reacting the reaction mixture contains three moles of carbon disulfide (CS_2) and two moles of sulfur. Write a balanced equation for this reaction.

   SCORING: (-3) pts. if excess reactant treated as product; (-1) pt. if equation balanced but not in lowest terms; (-1) pt. if reactant or product formula incorrect; no points for unbalanced equation

6. The molecular weight (molar mass) of Compound X is three times the molecular weight of Compound Y. What mass of X will have the same number of molecules as 21 g of Y?

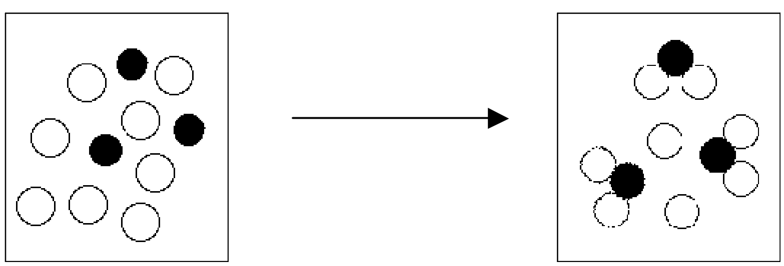
   SCORING: 3 pts. for correct answer; 2 pts. for explanation (via words or work)

7. A 25.0-mL sample of an acetic acid ($C_2H_4O_2$) solution (vinegar) is titrated with a 0.500 M NaOH solution. If 30.0 mL of the NaOH solution are required to reach the endpoint of the titration, how many grams of acetic acid ($C_2H_4O_2$) did the vinegar sample contain? Remember to show all your work.

$$C_2H_4O_2 + NaOH \Leftarrow NaC_2H_3O_2 + H_2O$$

   SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

8. The reaction of Element X (λ) with Element Y (○) is represented below.



   Write the equation that describes this reaction:

   SCORING: (-3) pts. if excess reactant treated as product; (-1) pt. if equation balanced but not in lowest terms; (-1) pt. if reactant or product formula incorrect; no points for unbalanced equation

9. For each of the following solutions' manipulations, please show all your work: (**SCORE** each part as one question=5pts.)

   (A) When 55.0 mL of a 0.25 M solution of maltose is diluted by adding 125.0 mL of water, what is the molarity of maltose in the final solution?

   SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

   (B) If 257 mL of a 0.75 M solution of maltose is reduced by evaporation to 195 mL, what is the molarity of the new solution?

SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

(C) If you combine 132 mL of a 0.85 M solution of maltose with 457 mL of a 0.24 M solution of maltose, what is the volume and molarity of the final solution?

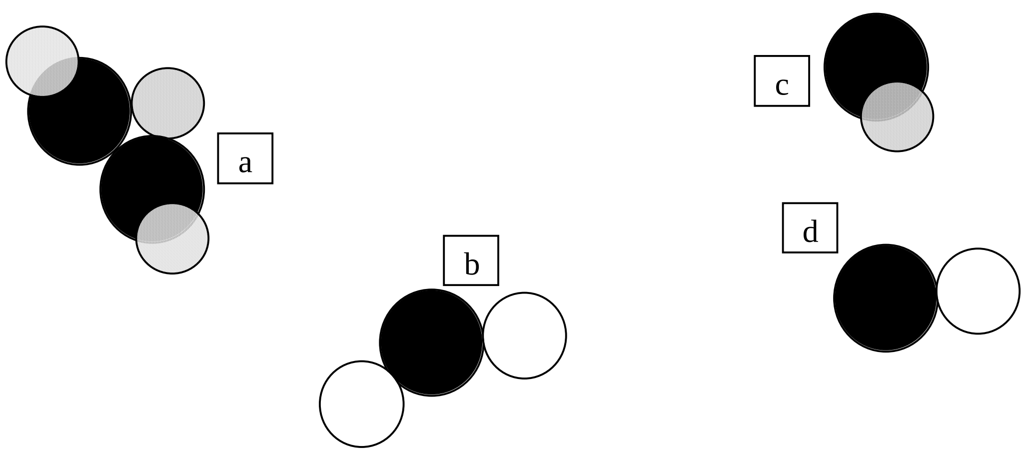
SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

10. When you mix 0.945 g of Sn and 1.834 g of I_2 in an appropriate solvent, 1.935 g of SnI_4, an orange solid, is formed. What are the theoretical and percent yields of SnI_4? Please show all your work. (**SCORE** 5 pts. for theoretical yield, 5 pts. for percent yield)

SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

11. Given that the white element weighs twice as much as the striped one, rank (from greatest to least) the percentage compositions of the black element in the molecules below. Please show all your work.

SCORING: 1 pt. each for c>a, a>d, d>b; 5 pts. for all correct



12. Assume that the reaction of rubidium (Rb) with these three acids takes place as shown and goes to completion.

(D) $2\ Rb + 2\ H_2O \Leftarrow 2\ RbOH + H_2$

(E) $2\ Rb + H_2C_2O_4 \Leftarrow Rb_2C_2O_4 + H_2$

(F) $6\ Rb + 2\ H_3AsO_4 \Leftarrow 2\ Rb_3AsO_4 + 3\ H_2$

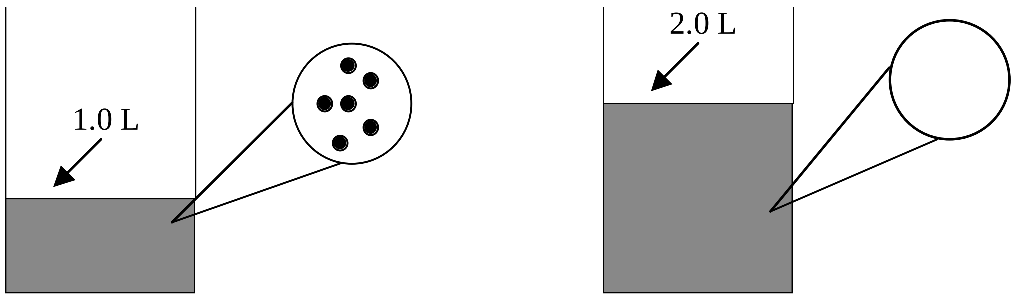
If an equal mass of rubidium (Rb) reacts with each acid, compare the yields of hydrogen (H_2) produced in each reaction.

SCORING: 1 pt. for each equality (all are equal); 5 pts. for all equalities

13. A 2.000 g sample of a Ni-Tl-Zn (nickel-thallium-zinc) alloy is dissolved in nitric acid. After the addition of excess HI (hydroiodic acid) to this solution, 1.750 g of TlI (thallium iodide), the only solid produced, is separated from the solution. Calculate the percentage of Tl (thallium) in the alloy. Please show all your work.

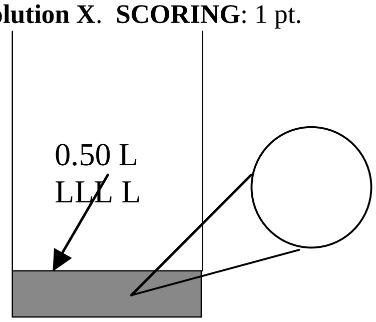
SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

14. **Solution S** represents a 1.0 L sugar solution. The dots in the magnification circle represent the sugar molecules. To simplify the diagram, the water molecules are not shown.



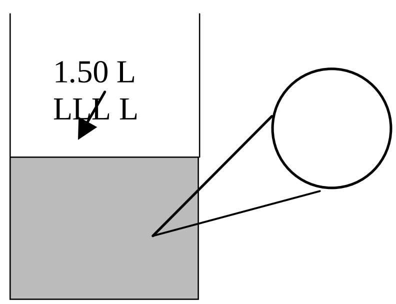
Solution S **Solution X**

(A) **Solution X** results from adding 1.0 L of water to **Solution S**. Draw the view of sugar molecules in the magnification circle for **Solution X**. **SCORING**: 1 pt.



Solution Y

(B) A fresh 1.0-L batch of **Solution S** is evaporated until only 0.50 L remains (**Solution Y**). Draw the view of sugar molecules in the magnification circle for **Solution Y**. **SCORING**: 2 pts.



Solution Z

(C) **Solution Z** was created by mixing **Solution Y** (0.50 L) with a fresh batch of **Solution S** (1.0 L). Draw the view of sugar molecules in the magnification circle for **Solution Z**. **SCORING**: 2 pts.

15. What is the empirical formula of citric acid, a sample of which contains 37.51% C, 4.20% H, and 58.29% O? Please show all your work.

SCORING: 1 pt. for each correct subscript; 1 pt. for correct formula format; 5 points for both format and subscripts correct

16. A 6.80-g coin was dissolved in nitric acid. Excess NaCl was added and 6.21 g of solid AgCl was produced. Calculate the mass percentage of silver in the coin. Remember to show all your work.

$$Ag^{+}(aq) + Cl^{-}(aq) \Leftarrow AgCl(s)$$

SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

APPENDIX J

POSTTEST-2 SCORING KEY

1. An amino acid has a molecular weight (molar mass) of 776.9 grams/mole and contains 65.34% iodine by mass. What is the number of iodine atoms per molecule of this amino acid?

   SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

2. What is the molarity of a 15.0 mL solution that contains 89.3 milligrams KBr?

   SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

3. A 25.0-milliliter sample of HNO_3 was titrated with standard 0.100 M NaOH solution. The endpoint was reached after 20.0 milliliters of the NaOH solution was added. How many grams of HNO_3 did the sample contain?

$$HNO_3 + NaOH \rightarrow NaNO_3 + H_2O$$

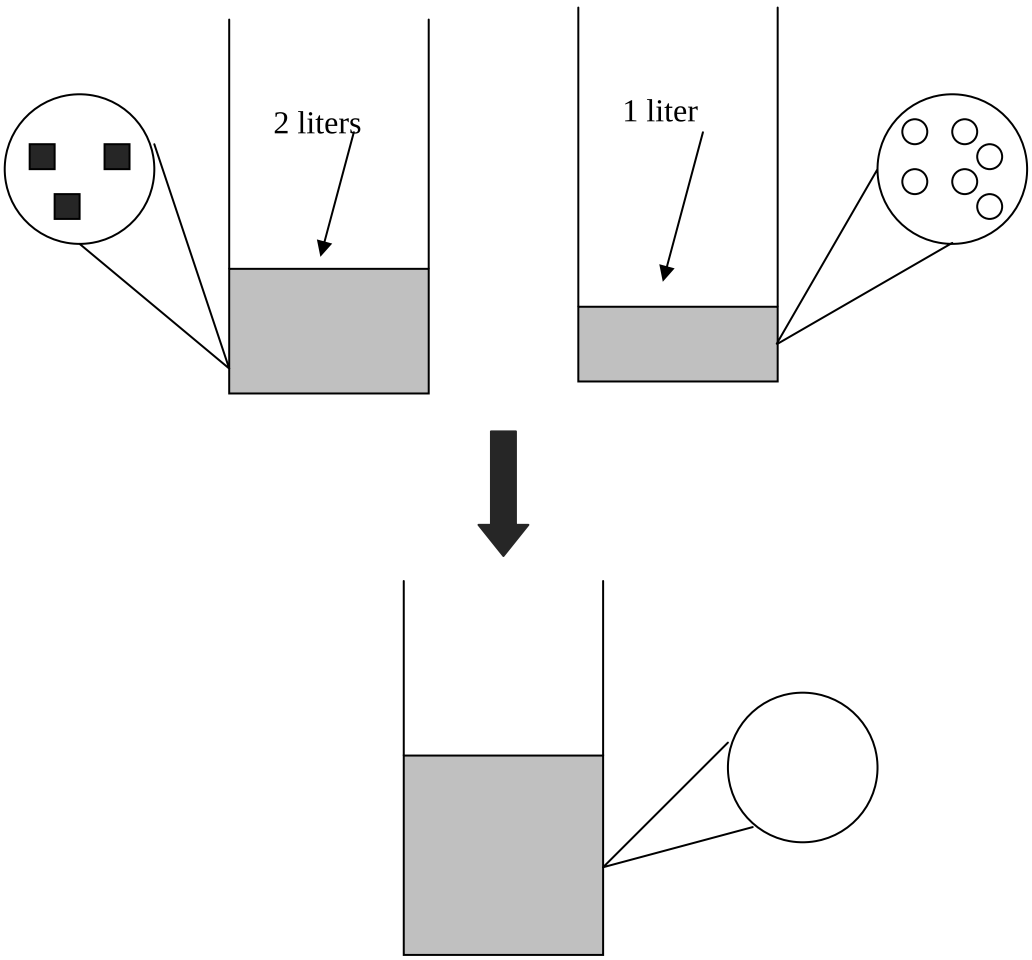
   SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

4. What masses of what substances remain after 54 grams of aluminum (Al) and 32 grams of oxygen (O_2) react to produce aluminum oxide (Al_2O_3) as the only product? Remember to show all of your work.

   SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

5. The contents of the two beakers below are poured into a third beaker. Draw the view of molecules in the magnification circle provided for the third beaker.

SCORING: 2 pts. for each number of correct shapes; 5 pts. if both numbers of correct shapes



6. A 6.16-gram sample of CCl_4 reacted with excess oxygen to form 3.4 grams of $COCl_2$ as the only carbon-containing compound. What was the percent yield of that product? Please show all your work.

SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

7. The formula for methane is CH_4. This means that, in methane, (circle all that apply)
   - A. for every 100 atoms of hydrogen there are 400 atoms of carbon
   - B. for every atom of carbon there are 4 atoms of hydrogen
   - C. for every gram of hydrogen there are 12 grams carbon
   - D. the compound is 25% hydrogen by mass
   - E. the compound is 80% hydrogen by mass

SCORING: 1 pt. for (B); 1 pt. for (D); 5 points for both (B) & (D); no credit for other choices

8. Assume the reaction of magnesium (Mg) with these three acids takes place as shown and goes to completion.

(1) $Mg + 2HCl \rightarrow MgCl_2 + H_2$

(2) $Mg + H_2SO_4 \rightarrow MgSO_4 + H_2$

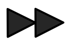
(3) $3Mg + 2H_3PO_4 \rightarrow Mg_3(PO_4)_2 + 3\ H_2$

If an equal mass of magnesium reacts with each acid, compare the yields of hydrogen produced in each reaction.

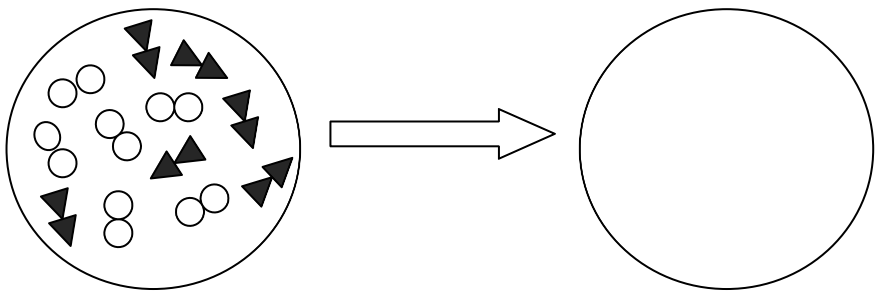
SCORING: 1 pt. for each equality (all are equal); 5 pts. for all equalities

9. The atomic weight of element A is twice the atomic weight of element B. What mass of B will have the same number of atoms as 32 grams of A? Please explain your answer.

SCORING: 3 pts. for correct answer; 2 pts. for explanation (via words or work)

10. Chlorine (Cl_2)  and iodine (I_2)  react to give ICl_3. (**X**) is a mixture of chlorine and iodine. (SCORING: Part A and Part B each worth 5 pts.)

(A) Draw the resultant substance(s) in (**Y**) after the reaction goes to completion.



(**X**) (**Y**)

SCORING: 1 pt. for each substance's correct amount; 5 pts. if all substance amounts correct

(B) Write the balanced equation that describes this reaction:

SCORING: (-3) pts. if excess reactant treated as product; (-1) pt. if equation balanced but not in lowest terms; (-1) pt. if reactant or product formula incorrect; no points for unbalanced equation

11. A compound of sodium, sulfur, and oxygen contains 29.08% Na, 40.56% S, and 30.46% O. What is the correct empirical formula consistent with the precision of the data? Remember to show all your work.

SCORING: 1 pt. for each correct subscript; 1 pt. for correct formula format; 5 points for both format and subscripts correct

12. The contents (A, B, and C) of three different bottles of fructose solutions were combined in a 1000-mL volumetric flask. The flask was then filled to capacity with distilled water. Solution A was 74 mL of 0.527 M fructose, solution B was 632 mL of 0.872 M fructose, and solution C was 139 mL of 1.16 M fructose. What was the final concentration of fructose in the volumetric flask? Please show all your work.

SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; (-2) pts. if did not dilute to 1000 mL; no credit for conceptual error or not answering question

13. A sample that contains only $SrCO_3$ and $BaCO_3$ weighs 0.800 g. When it is dissolved in excess acid, 0.211 g of carbon dioxide (CO_2) is liberated by the acid. What percentage of $SrCO_3$ did the sample contain by mass? Assume that all carbon in the original mixture is converted to carbon dioxide. Remember to show all of your work.

SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

14. A 2.00 g mixture of NaCl and $NaNO_3$ dissolved in water required 90.0 milliliters of 0.100 M $AgNO_3$ to react with all the chloride to form AgCl. What is the mass percentage of NaCl in the original sample? Please show all your work.

$$Ag^{+}(aq) + Cl^{-}(aq) \Leftarrow AgCl(s)$$

SCORING: (-1) pt. for significant figures error; (-1) pt. for arithmetic/units error; no credit for conceptual error or not answering question

APPENDIX K

POSTTEST-3 SCORING KEY

1. The molecular weight (molar mass) of Compound A is four times the molecular weight of compound B. What mass of B will have the same number of molecules as 20 grams of A? Please show your work and explain your answer.
SCORING: 3 pts. for correct answer; 2 pts. for explanation (via words or work)

2. The mass of a sulfur atom is twice that of an oxygen atom. The formula, SO_2, means that in a sample of sulfur dioxide (circle all that apply):

   A. The compound is 33% sulfur by mass.
   B. For every 100 atoms of sulfur, there are 200 atoms of oxygen.
   C. The compound is 50% oxygen by mass.
   D. For every 2 grams of oxygen, there is 1 gram of sulfur.
   E. For every atom of oxygen, there are two atoms of sulfur.

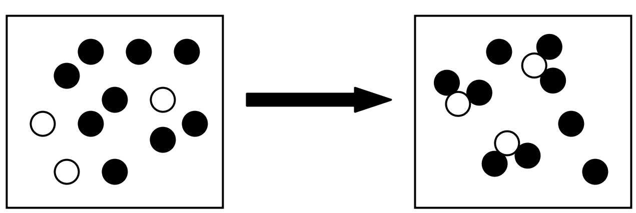
   SCORING: 1 pt. for (B); 1 pt. for (C); 5 pts. for both (B) & (C); no pts. for any other responses

3. The mass of a mole of molybdenum (Mo) atoms is eight times that of a mole of oxygen (O) atoms. Arrange the following oxides of molybdenum in order from least to greatest percentage by mass of molybdenum. Please show all your work.

   MoO_2
   MoO_3
   Mo_2O_3
   Mo_2O

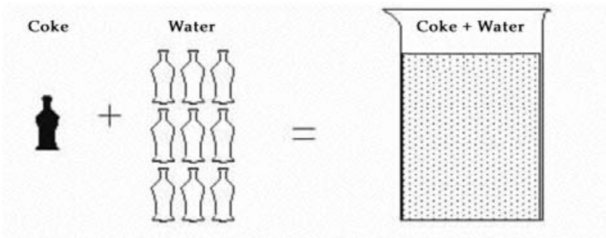
   SCORING: 1 pt. for each oxide in the correct order ($MoO_3 < Mo_2O < MoO_2 < Mo_2O_3$); 5 pts. for all correct

4. The reaction of Element W (○) with Element D (λ) is represented below.



Write the balanced equation that describes this reaction.
SCORING: (-1) pt. if reactant or product formula incorrect; (-1) pt. for not in lowest terms; (-3) pts for excess reactant on product side; no points for unbalanced equation

5. You are mixing the contents of a bottle of Coke with the contents of nine bottles of water of equal volume. The concentration of sucrose in the Coke is 1 M. What is the final concentration of sucrose in the beaker? Explain how you determined your answer.



SCORING: 1 pt. for units in "M"; 1 pt. for "1" in numerator; 3 pts. for "10" in denominator (total final volume is 1 bottle + 9 bottles=10 bottles)

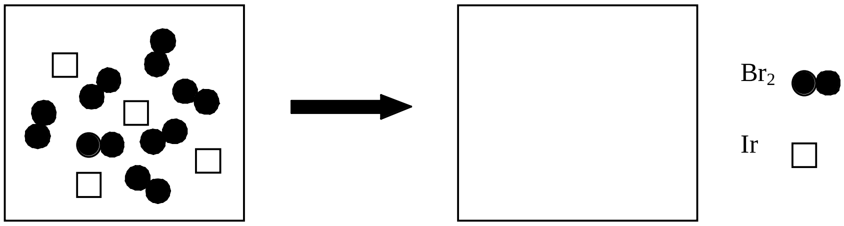
6. Calcium carbonate (chalk, limestone) reacts with acid to form a calcium salt, carbon dioxide, and water. Assume that the reaction of calcium carbonate with these three acids takes place as shown and goes to completion.

(A) $CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O$
(B) $CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + CO_2 + H_2O$
(C) $3CaCO_3 + 2H_3PO_4 \rightarrow Ca_3(PO_4)_2 + 3CO_2 + 3H_2O$

If an equal mass of calcium carbonate ($CaCO_3$) reacts with excess amounts each acid, compare the yields of carbon dioxide (CO_2) produced by each reaction.

SCORING: 1 pt. for each equality (all are equal); 5 pts. for all equalities

7. Figure (A) represents a mixture of iridium atoms and bromine molecules in a closed container. Assuming the reaction goes to completion ($2Ir + 3Br_2 \rightarrow 2IrBr_3$), draw what the mixture looks like in Figure (B) after reacting.



(A) (B)

SCORING: 1 pt. for each substance's correct amount; 5 pts. if all substance amounts correct

8. Hydrochloric acid and potassium hydroxide react to form potassium chloride and water:

$$HCl + KOH \rightarrow KCl + H_2O$$

If the molarity of an HCl solution is twice the concentration of a KOH solution, compare the volumes of each solution needed to react completely. Please show all your work.

SCORING: 3 pts. for correct answer (need 2x vol of HCl); 2 pts. for explaining or showing inverse relationship)

9. Magnesium nitrate and potassium hydroxide react to form magnesium hydroxide and potassium nitrate according to the following chemical equation:

$$Mg(NO_3)_2 + 2KOH \rightarrow Mg(OH)_2 + 2KNO_3$$

Assuming the reaction goes to completion, determine the number of moles of each substance remaining when 2 moles of magnesium nitrate and 2 moles of potassium hydroxide are mixed in a closed reaction vessel. Please show all your work.

SCORING: 1 pt. for correct amount of each substance; 4 pts. if all correct; 1 pt. for mentioning or showing limiting reactant by work

10. Two different non-reacting sugar solutions are mixed: 100 mL of 1.0 M glucose and 400 mL of 0.1 M fructose. What is the molarity of each sugar in the final solution? Please show all your work.

SCORING: 2 pts. for correct answers (1 each for glucose and fructose); 2 pts. for correct setup for each sugar; 1 pt. for total final volume of 500 mL

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