INTERACTION OF LEARNING APPROACH WITH CONCEPT INTEGRATION AND

ACHIEVEMENT IN A LARGE GUIDED INQUIRY ORGANIC CLASS

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A study was conducted to investigate the relationship of students’ concept integration and achievement with time spent within a topic and across related topics in a large first semester guided inquiry organic chemistry class. Achievement was based on evidence of algorithmic problem solving; and concept integration was based on demonstrated performance explaining, applying, and relating concepts to each other. Twelve individual assessments were made of both variables over three related topics – acid/base, nucleophilic substitution and electrophilic addition reactions. Measurements included written, free response and ordered multiple answer questions using a classroom response system. Results demonstrated that students can solve problems without conceptual understanding.

A second study was conducted to compare the students’ learning approach at the beginning and end of the course. Students were scored on their preferences for a deep, strategic, or surface approach to learning based on their responses to a pre and post survey. Results suggest that students significantly decreased their preference for a surface approach during the semester.

Analysis of the data collected was performed to determine the relationship between students’ learning approach and their concept integration and achievement in this class. Results show a correlation between a deep approach and concept integration and a strong negative correlation between a surface approach and concept integration.
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CHAPTER I

INTRODUCTION

Statement of the Problem

In the last 25 years our society has become more complex. Technology and globalization have exponentially grown information, which is literally available at our fingertips. Educational goals have evolved from transferring simply knowledge to students, to developing students’ critical thinking capabilities. Covering all knowledge in any given field is no longer a possibility; now our responsibility, as educators, is to help our students understand the fundamental concepts of our field and develop the “intellectual tools and learning strategies” that will aid their own learning in the future. This will enable students to achieve their full potential in whatever area they choose (Bransford, Brown, & Cocking, 2000).

Our strategy in educating scientists has been one of identifying and selecting talent from capable students showing an interest in science, rather than developing scientists from the population reaching the doors of our colleges and universities. In recent years there is increasing concern regarding the large number of capable students who choose careers outside science. Our strategy has shifted from selecting from those arriving at college with an interest in science to creating an interest in science, and helping those students develop the skills they need to compete in the global scientific community. However, the depth of their knowledge has been questioned.

Scientific education in the United States has been criticized for overemphasizing learning facts, which results in our students spending less time exploring and testing big ideas (Project, 1989). Critics accuse American science of “being a mile wide and an inch deep”
(Schmidt, McKnight, & Raizen, 1997). Rigid curricula, which specify numerous procedural objectives to be mastered, do not help the student see the connections of an individual concept within the larger disciplinary framework. It is this framework, and the interconnections of concepts, however, which is essential to achieving an integrated understanding in any discipline (Bransford et al., 2000).

Novak (2002) has expressed concern over higher education’s emphasis on rote memorization, suggesting that recall of answers for tests promotes verbatim rote learning (a type of learning representative of factual knowledge). Unfortunately, most of this “knowledge” soon becomes irretrievable from long-term memory, and, worse, even if recalled, seldom can the learner apply the knowledge in new or otherwise different contexts, such as novel problem-solving. This inability to transfer knowledge is sometimes referred to as “situated learning.” Thus much of the “high achievement” in terms of grades at our best universities may be considered fraudulent or inauthentic (Edmondson & Novak, 1992).

Even intelligent students who are motivated, high achievers become dissatisfied with their understanding of scientific concepts (Champagne & Bunce, 1991). Some students in college chemistry courses are frustrated because, in spite of earning high grades, they cannot explain basic concepts behind their achievement because much of their learning is algorithmic, begging the question: Do students fail to learn meaningfully because of the way we teach or because of the way students’ approach learning?

**Challenges of Large Lecture Classes**

Expository learning from the “sage on the stage” has been an educational tradition. Large enrollment lecture classes are cost effective for universities because they move large
quantities of students through lower division courses with a minimal expense and time. Given these economic realities, the large lecture format is not likely to be replaced in the near future (Cooper, 1995), except possibly by distance learning, which is even more cost efficient. Where the face-to-face faculty to student ratio makes the large lecture hall cost efficient, the trend has been to reduce face-to-face interaction completely. Asynchronous distance learning may be appropriate for some students and some courses, but many students need the supportive learning provided by face-to-face courses, particularly in the sciences. Large lectures provide a balance of economy while providing students the advantages of face-to-face interaction. Given the current economic situation and administrative popularity of large lectures, what can we, as educators, do to improve this learning environment?

Many students lament that the large enrollment classes are not the most effective way of learning (Zoller, 1993). Student anonymity in the class may create apathy, sometimes resulting in low attendance and increased student withdrawals (Dougherty et al., 1995). The lecturer may explain concepts, step-by-step problem solving tactics and answers, but by what process does this knowledge transfer to the mind of the student? Student remains responsible for working outside of class to better absorb what they have been taught in class, but is the current norm the best way?

Is student learning as successful as possible in this environment? In these large classes (and small classes as well), even experienced instructors may not have a true sense whether their students are learning meaningfully or just reproducing patterned responses (Mazur, 1999). Students may memorize what they have been “taught” because they lack the necessary conceptual understanding not to. Students often maintain misconceptions, of which instructors
are not aware. The instructors’ awareness must come from student feedback, preferably provided before graded assessment. Meaningful feedback requires asking questions to determine what their students know and don’t know. Technology’s increased availability, such as student classroom response systems (clickers), provides a critical opportunity for bilateral feedback between instructors and students, provided, however, those questions must be asked in a way that elicits a deep response and time is allowed for reflection.

Commonly, students play a passive role in the classroom, which may also make it more difficult for students to learn meaningfully in large enrollment classes. Cooper (1995) suggests that making this learning format more active for students is critical to improve meaningful learning. Cooper advocates using cooperative learning groups and the National Research Council recommends using technology such as clickers (Bransford et al., 2000).

Large class instructors are concerned with qualitative learning in their classes, and many look to technology to assist their students. Presentation software such as PowerPoint™ has replaced chalkboards and “clickers” have replaced hand-raising. Class Websites and electronic homework provide more active learning and feedback outside of class. All of these measures, if used properly, can impact learning; however because of the reduced personal interaction between instructor and student, learning in a class of 250 students remains more challenging that in a class of 25.

Challenges of Learning Organic Chemistry

Aside from the challenges of large classes, there are challenges specific to learning organic chemistry. The discipline is highly theoretical and abstract. The typical sophomore course is content intensive, full of symbolism, and requires spatial visualization skills. Reaction
mechanisms, which are used to understand the general chemical phenomena in reactions, are themselves a new language for the student. The common course organization is built around functional groups rather than general chemical principles that relate them, so it is difficult for students to connect these principles between textbook chapters. The assessment techniques used to measure learning may promote rote memorization rather than deeper quality thinking.

Forty years ago the main objective of organic chemistry was to synthesize compounds, therefore teaching focused on rote memorization of reactions that could be used in synthesis. Since then the number of reactions, reagents, reaction conditions, functional group transformations, and spectroscopy introduced in the sophomore course has increased enormously, which further encourages rote memorization, but making that difficult to accomplish by sheer volume of material. Few reactions have been discarded from the curricula so students still memorize reagents that are not used in the current day laboratory. As reported by Zurer (2001), one professor speaking at a symposium, said: “The typical organic curricula are not very flexible… . We've got so much we're expected to cover that we've developed this 'damn the torpedoes, full speed ahead' mentality. We're covering the material, but covering it doesn't guarantee that the students are learning it.”

Bruner (1966) believed that instruction should focus on helping students learn in ways that lead to understanding and subsequent transfer of that knowledge to new situations. In the last forty years, reaction theories have progressed substantially -- enabling organic chemistry to be taught in ways that facilitate general conceptual understanding. Since theories inform how reactions occur, it is no longer acceptable for a student solely to be able to predict the products of a reaction. Now a student must understand why one process is more likely than another
(Libby, 1995). The theoretical emphasis transformed organic chemistry into a more abstract and symbolic discipline. These two attributes alone demand complex thinking processes.

Because synthesis was the original focus of the course, the course has traditionally been organized around functional groups. Each chapter focuses on one functional group at a time – its physical properties, how to synthesize it, and what reactions it undergoes. Connecting chemical similarities among functional groups is not emphasized. The underlying set of chemical principles, which determines the chemical reactivity of these groups, is weakly connected chapter to chapter, if at all.

During the 1970s the organic curriculum subcommittee of the American Chemical Society’s (ACS) Division of Chemical Education met to agree on a list of “standard” organic course content. The committee discussed whether or not the course could be organized around principles rather than topics. The committee ultimately published two lists: one based on topics (functional group approach) and the other on principles (S. C. Bunce, 1972; Butler, 1976). Since then there have been attempts by several authors and publishing houses to reorganize the course around reaction mechanisms, molecular potential energies, or electron densities, but most of these books reverted back to the functional group organization after a few years; for example, Bruice’s textbook, third (2001) and fourth (2004) editions. Textbooks succeed through large research universities’ adoptions. These universities have high enrollments and large lectures, but have been resistant to curricular organizational change.

Educators have not achieved consensus regarding what the standard course should or should not include. Duis (2008) reports that in 2007 the ACS issued a statement that there was no need for standards “because there are many organic chemistry textbooks whose contents
provide a sound basis for organizing an introductory organic chemistry course”. Since then Duis surveyed 23 experienced organic educators regarding what concepts they considered important in the course and which were most difficult for their students. No single concept was named as fundamental by all of those surveyed. “Ultimately, there is more variation in the educators’ ideas about the fundamental concepts of organic chemistry than there are similarities” (Duis, 2008). Of the topics named as important by at least 20% of those surveyed, 48% of the educators named reaction mechanisms as difficult for students, 43% named acid base chemistry, 30% synthesis, 26% stereochemistry, and 26% resonance (Duis, 2008).

Many specific misconceptions named by the educators in Duis’ study are related to electron distribution: resonance as a fast exchange of electrons, movement of any bond or electron, electrons flowing toward negative charges, positive charges attacking atoms, arrows representing the movement of protons, and lack of relationship of symbolic level and the 3-dimensional particulate level (Duis, 2008). Another study has found that, after two years of college chemistry, misconceptions of the basic principles of hydrogen bonding persist. Students still think that “hydrogen bonds can be induced, intermolecular forces lead to reactions, or boiling breaks covalent bonds” (Henderleiter, Smart, Anderson, & Elian, 2001).

Organic chemists use a universal arrow pushing formalism to communicate and understand possible mechanistic pathways of organic reactions. This symbolism has been adopted by every major sophomore organic textbook in an attempt to help students understand the fundamental concepts in organic reaction theories. Organic textbooks vary greatly, however, and the symbols are not represented consistently across organic textbooks. Shortcuts are used, such as omitting symbols that are understood by organic chemists to be
implied, but would be useful in cuing a student and providing a clearer understanding of the reaction. Each textbook has its own set of shortcuts. One author suggests increasing the amount of detail shown and a consistent approach in textbooks and in class would help students understand mechanisms rather than memorize them (Friesen, 2008).

Another study suggests that teaching using reaction mechanisms does not increase students’ understanding of reactions. The study authors tested 14 chemistry graduate students’ conceptual understanding of sophomore organic chemistry mechanisms, each holding a minimum of a baccalaureate degree in chemistry. The researchers concluded that the arrows had “no physical meaning” for the graduate students and that they simply reproduced memorized sequences of arrows. The graduate students were unaware that the mechanisms are subject to the fundamental principles of chemistry (Bhattacharyya & Bodner, 2005). If this is the case, clearly we are failing to help our students develop the intellectual tools necessary in when confronting novel situations or in their future studies.

Need for Cognitive-based Curriculum Design

Do students fail to learn meaningfully because of the way they approach learning or because of the way we teach? If it is the way we teach, what basis should be used for course redesign? Knowing how people learn should be helpful in any conscientious process of redevelopment. Cognitive psychology, educational psychology, and neuroscience all contribute to research on how people learn. In the last decades all three disciplines converged on theories, such as schema formation theory, information processing theory, and neural network theory that can directly benefit and better inform education. These theoretical lenses can be used to examine existing practices and develop more effective ones.
Need for Research on Innovative Instruction

The National Research Council recommended areas of investigation that it deems important to the better understand learning. Of particular interest is the relationship of meaningful learning and the classroom environment. Researching successful creative educational practices, which foster meaningful learning through the underlying cognitive principles, can contribute to understanding why a pedagogy works and how students learn deeply. This research, in turn, leads to pedagogical improvements and wider adoption. This type of research is the kernel from which further cognitive research can grow (Bransford et al., 2000).

Scaling up a creative pedagogy from a small classroom to a larger one presents its own challenges. Studying how the innovative practice can be adapted to overcome design challenges is critical if change is to occur. The Council recommends research on the potential benefits of cooperative learning in the classroom and the adaptations that can be most beneficial. This is particularly difficult in very large lectures (Bransford et al., 2000).

Additionally the Council encourages study of the interrelationship between meaningful learning and student motivation to learn. The synergy between student motivation and predisposition to learning affects the depth of learning is important. But equally important is how classroom experience influences student motivation, if at all (Bransford et al., 2000).

Why are faculty reluctant to change their teaching dramatically? First, they want evidence that there is a problem with student learning in their classes. Why change if there is not a problem? Mazur (1999) suggests that even experienced instructors are not aware of what their students do not know, and therefore they have no reason to change (1999). Second,
faculty want evidence that any suggested change in pedagogy is better than what they are currently doing because it is especially difficult to change instruction if the students (and other faculty) respond negatively. Novak and Gowin (1984) found that approximately 5 to 20% of students respond negatively to instruction that fosters deep learning. About the same number of students will respond favorably, and the majority of students will respond negatively at first, but as they become comfortable with the new environment they become positive. According to Novak (Novak & Gowin, 1984) achievement scores drop for a period of time during the transition until the students learn what is required of them. The fall of achievement scores is disheartening for instructors (as well as students) and may be viewed negatively by the department in which they teach. With this much risk, why change?

**Course Selected for Study**

One way to improve education is to find and study practices that are successful. Another way is to design pedagogy based on theory of how people learn. In selecting the particular case for this study, three criteria were sought: (a) the pedagogy must be theoretically based on what is known about learning, (b) the course must be a scale up of a successful teaching innovation to the large lecture environment, and (c) the course must have prior demonstrated academic success. The course chosen for this study is a large class guided inquiry organic course that uses cooperative learning techniques based on a successful teaching pedagogy called process oriented guided inquiry learning (POGIL).

**Course Design and Theoretical Basis for Pedagogy**

Although the course content is organized around functional groups, the emphasis is on understanding how electron density influences the reactivity of functional groups. The
instruction used in this class is the process oriented guided inquiry learning or POGIL method. This pedagogy is based on constructivist theory and the use of a learning cycle. In a POGIL classroom students are actively involved in constructing their own knowledge through discussion of the questions with their peers, confronting their own misconceptions, and rearranging their knowledge to integrate the new concept with others already formed in their long-term memory. It is in agreement with well respected cognitive and education theorists – Piaget, Ausubel, and Vygotsky – social education experts such as Johnson and Johnson, and neuroscientists, as reflected the work of the science educator Anton Lawson. In this way the pedagogy is based on three disciplines that deal with research on learning – education, sociology, and neurobiology.

**POGIL Scale Up**

POGIL sophomore organic chemistry classes have been received well by students (Straumanis & Simons, 2008). However, active instruction using student-managed teams with just-in-time feedback presents a formidable instructional challenge in classes larger than 60 students. The course studied was carefully designed to overcome these challenges for a class of 250 students.

**Academic Achievement Pilot Study**

Pilot studies in previous years of this course demonstrated success in student achievement. Student exam data from courses taught by the same instructor were compared for classes using the lecture method and classes using POGIL. The POGIL classes demonstrated improved student exam scores with the new instruction method. Furthermore, student final exam scores from three concurrent sections with three different instructors using lecture,
lecture plus electronic homework, and POGIL — were compared. Figure 1 shows a graph of the results from this pilot study. On the common final exam the lecture only students scored the poorest, and the POGIL and lecture with homework appear equivalent (Ruder, 2008).

![Organic chemistry I Common Final Exam grades](image)

*Figure 1.* Comparison of first semester common final exam scores for POGIL and non-POGIL with and without homework — POGIL (Section 1) $N = 210$, Ave = 60, non-POGIL with electronic homework (Section 3) $N = 70$, Ave = 57, and non-POGIL without electronic homework (Section 901) $N = 160$, Ave = 48 (Ruder, 2008).

On a re-assessment of first semester topics given at the beginning of second semester, shown in Figure 2, the POGIL class demonstrated the highest test scores and least learning extinction. In addition to higher achievement scores, the POGIL class also demonstrated better student retention. Of the 240 students initially enrolled in the POGIL class, 88% took the final exam. Of the 200 students initially enrolled in the pure lecture course, 80% took the final exam. Of the 99 students initially enrolled in the lecture plus homework course, 71% took the final exam (Ruder, 2008). In light of the drop rate of roughly 12% for the POGIL class versus 20-29%
for the lecture classes and the increased achievement on the final examination, clearly the 240-student POGIL class had the best cost to benefit ratio of the three courses in this situation.

Figure 2. Comparison of delayed test scores for POGIL and non-POGIL sections with and without electronic homework. POGIL (Sections 1) N = 102, Ave = 57 and non-POGIL with electronic homework (Section 3) N = 25, Ave = 51 and non-POGIL without electronic homework (Section 901) N = 49, Ave = 25 (Ruder, 2008).

Purpose

This study is intended to better understand how time using in-class guided inquiry activities and the students’ learning approaches affect their achievement and conceptual understanding of organic chemistry in an active large class learning environment. Using in-class guided inquiry activities, the relationship of time spent within a topic and across related topics to achievement and concept integration are measured quantitatively through written and electronic assessment. Achievement is measured as problem solving and conceptual understanding is measured as students’ ability to explain, interpret and link related concepts (Liu, Lee, Hofstetter, & Linn, 2008). The relationship of beginning of course and end of course student learning approach is measured through the survey instrument, Approaches and Study
Skills Inventory for Students (ASSIST). Three characteristic learning approaches are measured as defined by the survey — deep, strategic, and/or surface (Entwistle & Ramsden, 1983). The relationship of these learning approaches to achievement and concept integration is determined by statistical analysis.

Research Questions

Question 1: What is the effect of the progression within a topic and across related topics on student achievement and concept integration when using a guided inquiry approach in a large first semester organic chemistry class environment?

Question 2: Are the students’ preferred learning approach affected by a semester-long experience in a guided inquiry first semester organic chemistry class?

Question 3: What is the relationship between students’ preferred learning approach (as measured by the ASSIST survey) and their integration and achievement in a large first semester organic chemistry class?

Definition of Terms

Achievement: Ability to solve problems using pattern recognition or an algorithm.

Active learning: A student-centered in-class learning environment in which students actively participate.

Algorithm: Use of a specific procedure to solve a problem based on using a general pattern to predict specific output.

Concept integration: Ability to explain, interpret, relate concepts and/or use concepts in a novel situation.
Cooperative learning: An active learning technique in which students work in small groups and receive rewards or recognition based on their group performance.

Deep learning approach: Seeking understanding with emphasis on making connections with existing knowledge.

Expository teaching: An in-class pedagogical practice of transmitting information to students through lectures.

Guided inquiry: A pedagogical practice in which students’ investigations are directed through instructional prompts.

Learning approach: Students’ organizational and study strategies for learning in an educational environment.

Learning cycle: A process used in teaching that involves three steps (a) exploration, (b) concept invention or term introduction and (c) concept expansion or application.

Meaningful learning: Ability to understand and communicate relationships among concepts.

POGIL: Process oriented guided inquiry learning is a pedagogy that uses guided inquiry activities in a cooperative learning environment.

Strategic learning approach: Awareness and emphasis on instructor’s goals and grading rubric.

Surface learning approach: Use of mechanical repetition and rote memorization techniques for learning.

Significance of Study

A study of the relationships among achievement, defined here as problem solving ability, and concept integration, defined as the ability to explain, interpret, and link related concepts, and learning approach, defined here as deep, strategic, or surface, is important for
several reasons. Firstly, understanding the relationships among achievement and concept integration can help inform curriculum design to encourage deeper and more meaningful learning in organic chemistry. Secondly, understanding the effects of an active guided inquiry learning environment on students’ learning approach can help evaluate strategies to improve students’ motivation to learn. Finally, understanding the relationship of students’ learning approach to achievement and concept integration may help predict what learning styles are most effective for deep, meaningful learning.
CHAPTER II

LITERATURE

Introduction

Many students do not learn meaningfully, with deep understanding of basic concepts and an understanding of their relationship to each other. They often have difficulty with chemical reasoning because they do not have the necessary conceptual understanding to support their thinking. In some cases critical thinking may not occur because the process has not been taught. Achievement is the accepted measure of success but often students can succeed on achievement problems without conceptual understanding as evidenced by a recent research study in organic chemistry (Bhattacharyya & Bodner, 2005).

This chapter provides a literature review in three areas – the theoretical basis of how learning occurs, pedagogies that are based on those theories, and students’ attitudes and approaches to learning. These three areas are important to understanding and answering the question: Do students fail to learn meaningfully because of the way instructors teach or because of the way students approach learning?

Theoretical Perspective

*Meaningful Learning and Cognitive Structure*

*Cognitive Development*

Jean Piaget was a Swiss developmental psychologist who studied learning in children outside the instructional environment. His work in two areas is important to this study – cognitive developmental stages through which a person progresses as they age and his theories regarding how learning occurs.
Piaget (1950) initially proposed that people go through four stages of cognitive development. The last two stages, which occur during or after adolescence, are of interest to college educators. During the third stage, the concrete stage, students understand ideas through physical objects or their models. Students are unable to imagine things they cannot see, such as an atom, until they reach the formal stage, when theoretical thinking is possible (Piaget, 1964). In the formal stage students can think in the scientific “if, then, therefore” mindset which is the basis of scientific thought. Piaget’s initial classification of four stages has been modified to include transitional stages. A fifth stage, post-formal or theoretical, has been proposed (Lawson & Renner, 1975). This stage is characterized by abstract thinking, which does not have a basis in concrete objects. Not all persons reach this cognitive stage, which does not occur before later adolescence (Lawson, 2003). These developmental levels are important to students’ ability to understand organic chemistry, a theoretical and abstract subject using hypothetico-deductive reasoning. If students cannot reason at this level they will not be able to understand unless they are taught “formal” reasoning as part of their instruction.

Cognitive Structure

Piaget’s second important contribution to this study is his theory of personal intelligence. Piaget (1970) classified knowledge as declarative or procedural. Declarative knowledge is conceptual knowledge – things that we know about something and are able to verbalize. Procedural knowledge is the knowledge about how something is done and is often automatic. Declarative knowledge is organized into an “operatory scheme” that includes groups of related concepts (Piaget & Inhelder, 1969). It is this cognitive structure that provides meaning and organization to a person’s knowledge. Without this organization a person cannot
retrieve and utilize relative information when needed or apply known concepts to new situations. (Sternberg, 2006).

This mental unit, renamed “schemata,” is an organized group of concepts that are related by classes and characteristics. Piaget proposed that schema are changed as a result of experience through a continuous adaptation processes of assimilation and accommodation. When people observe something that is new to them, they “assimilate” the new idea by fitting it into their previously existing knowledge in a schemata. If they encounter something that is contrary to what they already know, they are in “disequilibrium.” They must either modify the incoming information that challenges what they know or their schema that conflict with the new information. This later process is known as “accommodation.” If the cognitive dissonance cannot be resolved, then the information is either not stored at all or stored as isolated, fragmented knowledge, making it difficult to retrieve later, essentially rendering it unusable (Piaget, 1977a).

Since Piaget’s seminal work cognitive psychologists have proposed at least six models of cognitive declarative knowledge structure, however a common element to each is that the unit of symbolic knowledge is a concept (Bruner, Goodnow, & Austin, 1956). These concepts are organized into categories that can be prototypes, exemplars, hierarchically organized networks, or schema. Schema are mental frameworks of interrelated concepts in a meaningful organization (Bartlett, 1932). Schema can include other schema, encompass general facts that vary slightly from one context to another, and can vary from concrete to abstract (Rumelhart & Ortony, 1977). Schema organize relationships among concepts, attributes within concepts and
between concepts, and concepts in specific contexts (Komatsu, 1992). Those relationships permit causal higher order-thought — the “if, then, therefore” of scientific thinking.

Scripts are descriptions of sequences of events for a particular situation and are used to handle everyday tasks. They do not change and are not adaptable to novel situations, an important difference from schema (Sternberg, 2006). Scripts are algorithms that are useful in handling routine situations such as writing a structural formula — connect the carbons with bonds, make sure there are four bonds to each carbon, etc. — whereas schema allow critical thinking in novel situations.

*Processing Information*

Information processing occurs in working memory so limitations in working memory restrict our ability to process information. George Miller’s (1956) work demonstrated that working memory has a limited capacity of $7 \pm 2$ chunks of information. The chunk represents a unit of information that has meaning to the person’s thinking. By placing multiple pieces of data together as one meaningful chunk, the person can increase the limited capacity of short-term memory (Sternberg, 2006). The working memory holds information while it is being processed through reasoning, so if the information has many individual pieces to hold in memory, then the person cannot process the data and information overload results. Chunking decreases the strain on the limited capacity of short term memory by combining individual pieces of information into unified concepts (chunks) thus appearing to expand short-term memory. Chunking techniques are commonly used by chemists. For example, a carbon atom bonded to three hydrogen atoms and any other fourth atom is one mental chunk referred to as a methyl
group. This enables an organic chemist to hold a large amount of information in working memory at one time so that it can be processed.

Information is processed in working memory through reasoning — comparing, contrasting, and interpreting incoming information. However, before the information can be processed it has to reach working memory. There are several cognitive models of information processing — some developed to explain certain types of thinking. Rumelhart and Ortony (1977) proposed the schematic representation of knowledge. Johnstone’s (1997) interpretation is shown in Figure 3. In this model, a perception filter screens out irrelevant incoming sensory information prior to entering working memory. Most of the filtering is unconscious and continual, but some screening is done with conscious awareness. The filtering is based on our prior experiences stored in long-term memory, which include biases and misconceptions. This is the first step that can block learning. If the student is not attending to the information or the information conflicts with what the student already knows it will not enter working memory without further processing (Purves et al., 2008; Sternberg, 2006).

Figure 3. Schematic information processing model, adapted from Johnstone (1997).
Once in working memory, the information is processed with other relevant information, and an active process that involves rearrangement of the information, comparison to existing knowledge, and encoding for memory consolidation to long-term memory begins (Lawson, 2006). How this information is encoded is critical to its recovery (Purves et al., 2008).

The external representations must be converted to internal representations and associated with relevant existing knowledge. If the information is not coded correctly, or not associated with relevant information, it is fragmented and isolated from the schema network and may not be recoverable when needed (Lawson, 2006). Thus how the concept is stored and related to other concepts in a schemata is critical to the student’s ability to recover and use the information at a later time. This storage organization is one of the qualitative differences between expert and novices. For example, in organic chemistry there are subtle differences between a base and a nucleophile. Students must not only memorize, but also understand, the similarities and differences between the two to be successful.

*Expert versus Novice Cognitive Organization*

High levels of meaningful learning require that a network of schema to integrate new knowledge is already in place (Ausubel, 1963; Novak, 2002). Research suggests that the difference between novice and expert knowledge is the extent of the network connections. Experts not only have more knowledge than novices but it is also better organized (Chi, Glaser, & Rees, 1982). Therefore, meaningful learning involves qualitative changes — efficiently organized schema (Shuell, 1990).

These qualitative differences are demonstrated in studies of persons with different degrees of expertise. Those who have had no prior experience with the subject matter tend to
derive principles based on their everyday experiences with no scientific basis. Novices, those who have had some instruction in the subject, often use equations or rules to connect physical variables. They do this because they do not have well connected schema, since equations do not form a sound basis for schema organization. Experts most often use general abstract theories to organize and relate basic concepts to equations and formulae (Champagne, Klopfer, & Gunstone, 1982). The theories and principles governing the topic are integrated in such a way that experts see relationships between one general area and another (Chi, Glaser, & Farr, 1988). Experts can see patterns and relationships that novices cannot. This is evident in the comparison of concept maps developed by novices and those developed by experts (Herron, 1996).

For students to become more accomplished in a discipline they must have a thorough foundation of factual knowledge, an understanding how those facts and ideas fit into a conceptual network, and organized their knowledge in a way that enables easy retrieval from memory and application to new situations. Different representations of a problem can make it easy or difficult to solve. Experts can adapt representations for the best fit to a problem because they have well organized knowledge bases (Bransford et al., 2000).

Neurobiology Neural Network Theory

Theories of expert-novice cognitive organization and information processing are supported by what is known about brain physiology. Thinking changes the brain (Levy, 2007). The associations between concepts are generated in the related firing of neurons. In 1949 Hebb proposed a cellular description to explain learning and memory. If two neurons, differing in strength, synapse on another neuron and they fire together, the process will strengthen the
weaker neuron as well as the stronger neuron. Neurons that fire independently will weaken and eventually go dormant (Purves et al., 2008). Learning is the result of an increase in strength and number of synaptic connections; and pairing a weak new idea, with a more entrenched idea, will strengthen both through synchronous firing. Connecting concepts already known with new concepts strengthens the new one in long-term memory by associated coordinated neuronal firing (Lawson, 2003, 2006). This provides physiological support for cognitive psychologists’ theory that a new concept must be associated with other concepts in schema before it can be learned.

The brain processes incoming information by trying to match it with what the brain predicts from prior experience. In neural network theory this concept is known as “adaptive resonance”. If the new information matches expectations it resonates and is readily received, coded and stored in long-term memory based on common patterns. However, if the incoming information is not what the brain expects based on prior knowledge, it is not stored without further analysis. The subsequent search for another matching pattern is unconscious and, if successful, the incoming concept is coded and stored in long-term memory. The search is not random; rather the brain seeks to find relevant information in associative memory. If subsequent searches for resonance are not successful, then the incoming concept will not be stored without further stimulation (effort on the part of the learner). If the idea does not share a pattern with something already known, it can be stored in long-term memory only after careful attention that boosts the synaptic activity enough to allow recording into long-term memory (Lawson, 2003, 2006). This theory is the neurobiological parallel of the cognitive psychologists’ theories. One cannot meaningfully learn new information if it is not associated
with or conflicts with existing knowledge. Some modification has to occur to embed this new concept in the previously learned schema.

Cognitive psychologists and neurobiologists have theorized what happens internally to the learner — through neural network theory, information processing theory, schema development theory, and others. However, the learner is always influenced by the external environment. Educational psychologists have also addressed the role of the instructor and the learning environment.

*Educational Learning Theories*

**Social Learning**

A major theme of Lev Vygotsky's (1978) theory is that social interaction plays a fundamental role in the development of cognition. Students do not learn in isolation. Through verbalizing their thinking as they work, they monitor their own understanding and develop metacognitive skills. Thus by making their thinking transparent to their cohort, students learn metacognitive skills (Bransford et al., 2000).

Vygotsky proposed the concept of the “zone of proximal development” or ZPD. This zone represents the area between the students’ ability to problem solve on their own and what they can do with assistance — either from an expert or in collaboration with peers. If the students are taught at the level they know, they learn content only and not the critical thinking process. If they are taught at a level above their ZPD, they are unable to fully comprehend. Vygotsky proposed teaching students’ within their ZPD with the instructor as coach. The role of the instructor should be to determine what the students can do and coach them to a higher
level of understanding by providing both help and by asking questions. In essence this is creating a ladder or scaffold (Vygotsky, 1978).

Vygotsky’s (1978) work emphasized generalizations of concepts. Students’ conceptual understanding advances when new connections are made between concepts that result in the development of a higher generalized concept. Students use differences and commonalities among concepts to generalize to another concept that encompasses multiple ideas. This is the hallmark of expert knowledge.

Ausubel’s (1963) assimilation theory expanded the cognitive processes proposed by Piaget. In the creation of new knowledge, an example of a concept is “subsumed” by linking it with a concept already in long-term memory (Piaget, 1977a). Ausubel further differentiated subsumption into two types, “derivative” and “correlative”. Derivative subsumption occurs when an additional example is added to an already formed concept in an existing hierarchical knowledge structure. This occurs readily because the concept already exists in the cognitive structure (Ausubel, 1963). For example, it is relatively easy for a novice organic student to add carboxylic acids to the concept of an acid as a proton donor that they learned in general chemistry.

The second type of subsumption, correlative, is more difficult because it involves connecting or elaborating on a previously learned proposition – the new material just doesn’t fit in an existing category or the categories require refinement. For example, it is more difficult for students to connect the concept of a nucleophile with that of a base because it requires modification of the category or the addition of a more generalized hierarchical concept.
Ausubel further described a process, progressive differentiation, which occurs when a generalized concept gains more detailed specifics that differentiate it from other concepts. For example, a species is more likely to act as a base than a nucleophile if it has steric bulk. This enables the learner to fit the concept into the cognitive hierarchy. The process of pulling together of concepts and propositions to develop a more generalized cognitive structure based on hierarchy is called superordinate learning (Ausubel, 1963; Novak, 2002). For example, both nucleophiles and bases have high-energy electron pairs, a more generalized concept, which impact chemical reactivity. This type of learning is seen in the big picture thinking of experts and the basis of expert knowledge. It is the degree and extent of this cognitive structure that differentiates expert from novice knowledge (Novak, 2002).

**Constructivist Theory**

Piaget’s view is that learning is internal to the learner. Knowledge is acquired by the individual’s active mental process of reaching cognitive equilibrium via assimilation and accommodation (Piaget, 1977a, 1977b). The ideas of Piaget, Vygotsky, Ausubel and others have been used to form the educational theory of constructivism. Constructivists believe that meaningful understanding occurs through an individual’s personal and active reconstruction of the knowledge in their brain, integrating the new knowledge into their pre-existing knowledge (Herron, 1996). It is not the process of receiving incoming information through the senses that creates meaningful learning, but the process of interacting with the incoming information in the brain. Instructors cannot transfer knowledge directly to the student unless the learner actively participates in the learning process (Resnick, 1980; von Glasserfeld, 1981; von Glassersfeld.E., 1995).
**Meaningful Learning**

Meaningful learning implies understanding, which is different from “knowledge” in that it implies a “complex, multidimensional integration of information into the learner’s own framework”. Instead of reciting “facts” the learner is able to “explain, interpret, and apply” their knowledge, knows the limits of their knowledge, and can put it into a more general perspective (Tanner & Allen, 2005, p. 113).

Meaningful learning requires active effort on the part of the learner to incorporate new knowledge with already existing concepts into their mental framework of ideas. This includes relating these new ideas in a hierarchical system whereby the new knowledge is given meaning and perspective by the existing framework (Novak & Gowin, 1984).

In the 1960s Ausubel described meaningful learning as integration of non-verbatim, substantive new knowledge into a person’s cognitive structure. He described substantive learning as understanding the key concepts in the new knowledge. This integration is non-arbitrary — the learner must choose to associate the new knowledge within his or her cognitive structure. At the other end of the spectrum is rote learning. Rote learning is the arbitrary, verbatim, non-substantive incorporation of new knowledge into the cognitive structure (Ausubel, 1963, 1968). Meaningful learning is one of degrees. Instead of memorizing the exact words of the instructor, students may transcribe them into vocabulary more easily understood by themselves, but they may not yet understand the deeper concept. This would be an example that is not complete rote memory, but at that end of the spectrum (Ebenezer, 1992; Novak, 2002).
Does memorization always mean a surface approach is at work? The study of science in particular involves many details and procedures that may require an initial period of memorization before that information can be used on a deeper level. This type of memorization is difficult to distinguish from rote memorization for verbatim recall (Entwistle & Ramsden, 1983). More recently Entwistle classified three types of memorization: “rote memorization, memorization related to understanding, and memorization taking place before or after understanding” (Entwistle & Entwistle, 2003). Since higher levels of meaningful learning require a strongly integrated system of relevant concepts, some lower-level learning must logically occur first (Novak, 2002).

Three qualitatively different phases of learning have been proposed by Rummelhart and Norman. In the first, “accretion”, the brain encodes new information based on previously understood concepts. In the second, “tuning”, a slower schema modification process occurs based on testing the concept in different situations. In the third a brand new schemata is acquired that has little association to current concepts. This is called “restructuring”. These learning phases can overlap or occur out of sequence, however typically they begin with accretion (Shuell, 1990).

Achievement

Academic achievement is the most commonly accepted criterion for student success. Much of this achievement in the organic chemistry course is measured in terms of ability to solve common problems, such as proposing a reasonable mechanism for a reaction or predicting the stereochemistry of a reaction product. Achievement, accomplished through rote memorization or through algorithmic problem solving, represents learning at Developmental
Stages I and II in this study. Students can memorize that the reaction product of two functional
groups produces a third, and then apply a set of memorized rules and pattern recognition to
predict the product but this is not evidence of meaningful learning with understanding.
Conceptual understanding is a measure of meaningful learning and this understanding occurs
through integrating concepts into one’s schema.

*Concept Integration*

Concepts are “perceived regularities in events or objects, or records of events or objects
designated by a label (usually a word). . . . Meaning making proceeds when a new regularity is
perceived in events or objects, or records of events or objects, leading to concept formation
and/or the construction of new propositions” (Novak, 2002, p. 550). Concepts are combined to
form statements or propositions that exist in our brain as networks (Novak, 2002; Novak &
Gowin, 1984). When meaningful learning occurs the new concept is integrated into the
cognitive structure to some extent (Herron, 1996). The extent of integration depends partly on
how hard we consciously try to make connections. Students who choose to learn by rote will
not learn meaningfully regardless of pedagogy or instruction (Novak, 2002). Students cannot
truly understand unless a concept is connected to other knowledge understood by the student
or to real world observations (Smith, 1991).

There is evidence that student success integrating concepts depends on the type of
concept and the student’s cognitive level (Lawson, Alkhoury, Benford, Clark, & Falconer, 2000).
Concepts can be classified in order of increasing difficulty — descriptive, hypothetical, or
theoretical. The first are descriptions of a concrete object such as an acid. For example at the
concrete level, an acid is a substance that turns litmus paper red. The second type of concept,
hypothetical, requires an “if, then, therefore” idea, which may be concerned a concrete idea — if a substance turns litmus paper red, then it must be an acid, therefore it will react with a base and will no longer turn the litmus paper red. The third type, theoretical, involves concepts that students cannot see, touch or smell — for example, an acid is a proton donor. In organic chemistry nearly all concepts are theoretical. One study suggests that students’ Piagetian cognitive developmental level will limit which kinds of concepts can be easily learned by students. Students at the concrete level will not be able to integrate theoretical concepts until they transition to formal reasoning. Therefore it is important to encourage the development of critical thinking to foster formal reasoning so that students can meaningfully learning theoretical concepts (Lawson et al., 2000).

Differentiation between Achievement and Concept Integration

Achievement often precedes understanding. There is evidence that general chemistry students can arrive at a correct answer without understanding the underlying principles (Bunce, Gabel, Samuel, 1991; Gabel, Sherwood, and Enochs, 1984; Herron and Greenbowe, 1986, Nurrenbern and Pickering, 1987). There is also evidence that organic chemistry students can solve achievement problems without basic understanding (Battacharyya & Bodner, 2005; Henderleiter et al., 2001). Mechanistic arrows have significant meaning to an organic chemist. They signify electron densities, energy relationships, electron movement and bond formation. However to novice students they can be just arrows drawn between alphabetical letters with a couple of dots to alphabetical letters without dots or with + signs.

Achievement questions do not require conceptual understanding, but conceptual understanding may be used to solve achievement problems. Thus achievement questions
cannot differentiate between achievement and concept integration. Meaningful learning requires integration of multi-dimensional concepts into a learners’ expanding network of ideas, and this understanding allows students to use concepts and their relationships to explain, interpret, and apply their knowledge. When a student can answer the question “why” without citing a rule, they are on the way to deeper understanding. If they can “link, distinguish, evaluate, and organize their ideas about complex scientific topics”, they have attained a higher, more encompassing level of concept integration (Liu et al., 2008). Complex and deep understanding also implies students know both how their knowledge fits into a larger framework of ideas and the limits of their understanding (Tanner & Allen, 2005).

**Developmental Stages of Concept Integration**

As a student moves towards deeper understanding there may be common identifiable developmental stages that represent points along the continuum of concept integration. Many times the process of integration is not linear or serial — stages overlap. However, there are often concepts in organic chemistry that are learned via a common pathway. Some of the assumptions that could be made regarding a direct pathway are:

1. Students name a new concept before they can make sense of it.
2. As students develop some understanding, the new concept is characterized and identified.
3. As students try to fit the new concept into their network of ideas, they examine the new concept in relation to other concepts already known.

However, the boundaries and interrelationships between the new and
known concepts are fuzzy, so students make common errors in the relationships.

4. As students develop, the boundaries/relationships among concepts become clearer.

5. Understanding becomes deeper when students can fully explain the relationship of the new concept to several others. The new concept has found its place in their network.

6. Connecting concepts demonstrates an interrelated network of concepts, which implies a larger and more general view of the topic (Briggs, Alonzo, Schwab, & Wilson, 2006; Eilam, 2002).

Table 1 lists characteristics of achievement (as evidenced by problem solving ability) and characteristics of concept integration (as evidenced by ability to explain, interpret and apply concepts) for each of four developmental stages of learning (Briggs et al., 2006).
Table 1

Developmental Stages of Learning, adapted from Briggs, Alonzo, Schwab and Wilson (2006)

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Characteristics of Achievement and Concept Integration</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td>Solves problem incorrectly. Names concept but does not relate it to the problem.</td>
</tr>
<tr>
<td>II</td>
<td>Provides correct answer without ability to explain or identify concept involved. Concept may be understood but only in isolation.</td>
</tr>
<tr>
<td>III</td>
<td>Provides correct answer, can explain using a few concepts and can apply to new situation, but fails to see how concepts relate to a broader network of ideas.</td>
</tr>
<tr>
<td>IV</td>
<td>Provides correct answer including understanding of subtle and complex aspects of the problem. Fits the concepts into a hierarchy network.</td>
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</table>

Theoretical Perspective Summary

The fields of neurobiology and developmental, cognitive, and educational psychology have advanced similar theories of meaningful learning. These theories propose: (a) meaningful learning occurs through concept integration rather than rote memorization (Ausubel, 1963; Piaget, 1977a), (b) concept integration begins with concept recognition in isolation and progresses as it is linked to existing concepts and integrated into the schema network (Piaget, 1977a; Vygotsky, 1978), (c) experts have a more extensive integration of concepts in a high quality, well organized, hierarchic network (Chi et al., 1988; Lawson, Abraham, & Renner, 1989), and (d) the higher generality understood, the deeper the learning (Ausubel, 1963).
Achievement, defined as problem solving, is the commonly accepted criteria for students’ successes, but students can achieve without having conceptual understanding (Bhattacharyya & Bodner, 2005; D. M. Bunce, Gabel, & Samuel, 1991; Gabel, Sherwood, & Enochs, 1984; Herron & Greenbowe, 1986; Nurrenbern & Pickering, 1987). Achievement represents progress through Learning Development Stages I and II; concept integration differs from achievement in that students are able to link related concepts, explain and apply them to novel situations that builds more extensive schema networks that are characteristic of Learning Developmental Stages III and IV (Liu et al., 2008).

To learn meaningfully, students must: (a) have a foundation of factual knowledge, (b) understand ideas in the context of a conceptual framework, and (c) organize concepts in ways that facilitate retrieval and application (Bransford et al., 2000). The diagram of the learning pathway provided in Figure 4 shows how instructors can encourage students’ movement through these developmental stages through the environment they provide in the classroom and their interactions with students.

Figure 4. Developmental learning progress from achievement to concept integration.
Theory-Based Pedagogy

Introduction

...a theory of instruction should address four major aspects:

(1) learner’s predisposition towards learning,

(2) the ways in which a body of knowledge can be structured so that it can be most readily grasped by the learner,

(3) the most effective sequences in which to present the material, and

(4) the nature and pacing of rewards and punishments (Bruner, 1966).

An instructional design based on Bruner’s (1966) suggestions supports students by helping them make accurate connections and extensions between concepts, and to build hierarchical schema networks. The questions raised by Bruner’s second and third points, the most effective sequence of the material and its structural form that can improve comprehension by the learner, have been discussed in the literature. Cognitive structural organization of experts is dissimilar among different disciplines. Science experts’ cognitive organization is much different than that of history experts (Bransford et al., 2000). Thus no one cognitive organization works for all disciplines. Within a discipline, cognitive structures vary greatly between experts and novices (Chi et al., 1982).

A recent study using knowledge space theory found the cognitive structures of experts and novices in organic chemistry are very different from one another as shown in Figure 5. Experts use charge densities as a general concept in a hierarchy to explain lower hierarchical concepts, such as physical properties of compounds (boiling point and solubility) and chemical properties (acidic/basic and nucleophilic/electrophilic). Students however, begin learning with
concrete concepts, the physical and chemical properties — boiling point, solubility, and acids/bases — before adding theoretical concepts. The study results suggest students’ schema splits at that point into two isolated pathways — one using acid base characteristics to explain nucleophilic and electrophilic properties and the other pathway leading to the charge density concept. It seems that students learn the charge density concept last, and do not integrate it with nucleophiles, electrophiles, acids and bases until considerable knowledge space has been filled. The essential difference is that experts use a theoretical concept, like charge density, to explain a concrete one, like boiling point, whereas novice students understand the concepts as linear (Taagepera & Noori, 2000). Similar results were found with a study on organic chemistry students’ understanding of hydrogen bonding (Henderleiter et al., 2001).

Figure 5. Critical learning pathways for experts and novices (Taagepera & Noori, 2000).

Since curricula are developed by subject matter experts, the organization reflects the expert’s understanding rather than the novice’s viewpoint (Lawson, 2003). The expert’s
sequence and presentation of the material may make it difficult for students to make the correct connections between concepts, resulting in incorrect or incomplete schema formation, which leads to students’ misconceptions. Presentations of mechanisms in organic textbooks routinely utilize shortcuts, such as failure to show the lone pairs that form a new bond in the reaction. Textbook mechanisms also write + H₂O, + H⁺, - H⁺ or – H₂O above the reaction arrow instead of showing specifically how these species are involved in the reaction. These shortcuts are readily understood by experts, but not by novice students. Using consistent, clear and detailed mechanisms can dispel many conceptual misunderstandings by providing scaffolding for learning mechanistic language (Friesen, 2008).

Misconceptions are often very hard to dispel, even in the face of overwhelming evidence. The single most critical aspect of a concept is how it is categorized and associated in memory. Conceptual change, an important area of research, focuses on moving the concept from the assigned category to a more appropriate one (Chi, Slotta, & deLeuw, 1994). This is a difficult task; the best approach is prevention, by designing materials to help develop appropriate cognitive connections (Niaz, Aquilera, Masa, & Liendo, 2002).

**Learning Materials’ Structure**

*Scaffolding*

Questions that probe the learner encourage the development of accurate conceptual connections and promote student understanding. This form of “scaffolding” provides the opportunity for the learner to see new patterns in events or objects, recast their meaning, and form new meaningful propositions with existing relevant concepts in their cognitive structure (Davis & Linn, 2000; Novak, 2002). Scaffolding permits students to tackle more complex
problems than they could without it (Bransford et al., 2000) and to keep learning within the students’ zone of proximal development. Stretching the mind through scaffolding promotes the development of a more extensive conceptual network that provides students with tools to solve complex problems.

Instructors can train students to think deeply by scaffolding through prompting and probing questions. In a study of 8th grade science students the researchers found that probing questions could draw out deeper strategies from surface learners (Chin & Brown, 2000). Using timely scaffolded prompts can encourage student reflection and self-monitoring (metacognition) (Davis & Linn, 2000). Reflection through articulating ideas allows students to examine their understanding and discover holes in their schema. Scaffolding may prevent student misconceptions by permitting correct cognitive connections with first learning (Niaz et al., 2002).

Students develop metacognitive skills to guide their thinking through internal and external arguments of alternate explanations in the classroom and reflection on their thinking process (Rickey & Stacey, 2000). Given choice, control and personal responsibility students will learn more meaningfully (Baron, 1998; Lawson, 2003). Emphasis on metacognition should be integrated with discipline based content as this helps the student to learn independently (Bransford et al., 2000) and this can be accomplished with scaffolding.

Using scaffolding techniques was found to be a more effective learning strategy than pure discovery (Brown & Campione, 1994) and to provide better learning outcomes in terms of solving new problems than either discovery learning or “rule and example” learning (Gagne &
Brown, 1961). The scaffolding in this study is accomplished by using the Learning Cycle in the guided inquiry activities.

**Spiral Learning**

Simply covering material especially as an “extensive list of new ideas” will not necessarily produce conceptual learning. As a proponent of “spiral learning”, Bruner (1966) encouraged repeating themes and concepts in different situations. Teaching a concept in a variety of contexts is more likely to facilitate transfer of that concept to new situations and result in further generalization than if the student has only seen it in one context (Baron, 1998; Bransford et al., 2000). Thus if instruction uses an overarching theme, such as electron density, to explain base strength and then repeats that theme to explain nucleophilic strength, it will be easier for students to connect the ideas, and will be able to apply the electron density concept in other situations. This reinforces meaningful learning. In this study spiral learning is accomplished through activities using the learning cycle.

**The Learning Cycle**

If people learn by receiving new stimuli and trying to identify patterns, then hypothetico-deductive reasoning is the process by which students learn, and anything that teaches students how to do this better should make them learn more meaningfully (Lawson, 2006). It may be that some college students have not learned the process of hypothetico-deductive reasoning prior to college and therefore it needs to be taught. Research studies comparing problem-based learning and content-learning curricula found that students following problem-based curricula are more likely to adopt a deep approach and are less likely
to adopt a surface approach to studying than those who engage in content-learning curricula (Sadlo & Richardson, 2003; Wilson & Fowler, 2005).

The learning cycle includes three stages of student learning: (a) exploration phase, (b) concept invention or term introduction phase, and (c) conceptual expansion or application phase (Abraham, 2005; Abraham & Renner, 1986; Lawson et al., 1989). In the exploration phase the students are presented with data in some form and are asked to find patterns and attempt to explain the pattern with a hypothesis. In the second phase, concept invention, the new concept or term is introduced based on the students’ understanding gained during the exploration phase. Thus the reasoning in the first part of the cycle is inductive. In the third phase, application, the students use the new concept in different situations. This last phase involves deductive reasoning (Moog & Spencer, 2008). The Learning Cycle places inductive reasoning before deductive reasoning, paralleling the scientific method. Inquiry-based teaching in science courses “engages a student in the exact same questioning of one’s preconceptions and challenging of one’s own knowledge that is characteristic of both conceptual change and scientific habits of mind” (Tanner & Allen, 2005). Lectures and textbooks traditionally present content in the opposite direction – the larger generality first, followed by deduction of lower hierarchical concepts.

Neural network theory supports the Learning Cycle that is the basis of the classroom activities used in this study. The Learning Cycle is also based on Piaget’s theory of assimilation and accommodation (Abraham, 2008; Eakin & Karplus, 1974). Neural network theory predicts that the Learning Cycle should be effective because it involves students viewing new information and identifying patterns and drawing conclusions. If we teach students to reason in
this way, it should result in helping them learn. Thus, if a new idea can be connected to a previously learned idea, then the new idea is more likely take hold based upon both neural theory and schema formation theory. Using the Learning Cycle in the activities should enable students to integrate concepts more readily (Karplus & Thier, 1967; Lawson, 1999), and promote the development of meaningful learning. Several studies have found increased achievement with the use of the Learning Cycle (Eakin & Karplus, 1974; Lawson et al., 1989; Renner & Marek, 1990).

Learning Environment

POGIL

POGIL is a theoretically based pedagogy that uses guided inquiry activities that follow the Learning Cycle. The process by which students learn in POGIL is based on cooperative learning techniques, rooted in social learning theory. The teaching philosophy behind the POGIL practice is that students learn better when:

1. they are actively engaged and thinking in class;
2. they construct knowledge and draw conclusions themselves by analyzing data and discussing ideas;
3. they learn how to work together to understand concepts and solve problems;
4. the instructor serves as a facilitator to assist groups in the learning process;
5. the instructor answers no question that the students can reasonably be expected to answer themselves (Farrell, Moog, & Spencer, 1999; Moog & Farrell, 1997).

In small classes effective social learning occurs through student group behaviors that act as “phases of” student learning. In the four phases of POGIL learning, students (a) compare and
contrast their ideas, (b) reach a consensus understanding, (c) revisit their understanding when an inconsistency appears, and (d) reach out to group members having difficulty understanding.

Two additional aspects of learning in this environment are tutor and mentor bridges. A tutor bridge occurs when a student asks another group member for clarification and explanation. The mentor bridge occurs when the group receives guidance from the instructor (Daubenmire, 2004; Daubenmire & Bunce, 2008). Guidance from the instructor can also be described as coaching which has been shown to be effective in making students’ thinking visible to themselves (Bransford et al., 2000).

In large classes of more than 100 students, the challenges of classroom management reduce the amount of social learning that can realistically occur. Modifications have been made to adapt the small classroom POGIL techniques to large classes (Ruder & Hunnicut, 2008; Yeziersk et al., 2008), however, the intimacy of a small classroom is difficult to duplicate. Despite the reduced social learning opportunities in large classes, students are still expected to develop more extensive cognitive networks and organization with the use of scaffolded in-class activities that incorporate the Learning Cycle. These results are somewhat in conflict with a study by Mason and Verdel (2001) who used the same intervention with a group of at-risk students split into either a class by themselves or incorporated into a large general chemistry lecture class. In this study it was reported that the at-risk students integrated in a large lecture class performed at a higher achievement level than those in the smaller class. One of the possible reasons for this success was that in the larger class there were more opportunities to benefit from peers with various levels of experience and ability.
Comparison studies in large classes have either shown no significant differences between POGIL and non-POGIL students, or that POGIL students retain more knowledge (Lewis & Lewis, 2005; Perry & Wight, 2008; Straumanis & Simons, 2008). Such conflicting results prevent a clear vision of POGIL’s effectiveness in large classes. Additional research on the effectiveness of POGIL is underway.

Active Learning in Large Classes

Lecture can hinder students from developing deep meaningful learning (Zoller, 1993). Large lecture classrooms do not necessarily provide a stimulating environment that engages students. Students can remain passive in large classrooms where they are anonymous and are not required to interact with peers or instructor. Some students who initially believe they don’t want to learn deeply change their minds when placed in an active, stimulating environment (Ward & Bodner, 1993).

Zoller (1993) suggests that large lecture classes are appropriate for students with lower order cognitive skills who desire to learn facts, but students with higher order cognitive skills need teaching strategies that focus on developing critical thinking – and these require in-class active participation of the student (Zoller, 1993). Since organic chemistry requires higher order cognitive skills, large lecture classes can be more challenging for this course than small classes.

Instructors have been successful in making large lectures more active. POGIL has been adapted to large classes (Lewis & Lewis, 2005; Ruder & Hunnicut, 2008). Peer-led guided inquiry has been demonstrated successfully in general chemistry (Lewis & Lewis, 2005) and inductive cooperative learning has been successful in large chemical engineering courses (Felder, 1996).
Two different philosophies of instruction for active learning in a large organic class can be found in the literature (Paulson, 1999; Ruder & Hunnicut, 2008). In large POGIL classes basic concepts are presented in class activities to assure they are understood by students. Students are subsequently assigned more advanced application problems for out-of-class work. This is to assure they understand the basic concept and develop critical thinking skills with more advanced problems. A second philosophy is to assign student reading prior to class (use of Ausubel’s advance organizers) and assume that the students understand basic concepts based upon this reading when they arrive in class. In this type of class, the instructor can focus on more advanced concepts with in-class activities (Paulson, 1999). However, students often have difficulty understanding the basic concepts in organic chemistry through reading. Some student-to-instructor feedback would be needed to verify the understanding of the basic concepts before progressing to advanced topics that use those concepts.

Interaction in a Large Classroom

Often one of the key differences of a large class from a small class is the degree of feedback between students and instructor. Timely feedback from the instructor on student performance is considered a hallmark of good instruction but is difficult in a large classroom. There are two requirements for an instructor to provide feedback that is helpful to the students: (a) the instructor must know what the students are thinking, and (b) the students must utilize the feedback given to them.

In a small POGIL classroom the instructor monitors learning by circulating among student groups to hear and see what they are doing during the guided inquiry activity. This helps the instructor learn what the students are thinking and then the instructor can provide
more focused feedback. Prior to classroom response technology (clickers), it was unrealistic for an instructor of a large class to monitor student understanding in real-time. Technology has helped make students’ thinking visible to the instructor and to themselves (Bransford et al., 2000) and today’s student response systems (clickers) and tablet PCs facilitate more real-time interaction between student and instructor than a paper-based classroom (Mewhinney & Zückerman, 2008; Ruder, 2008). In a large class using clickers to reveal what their students do not know allows the instructor to provide appropriate and timely feedback to students using a tablet PC and presentation software.

Students must do something with the instructor’s feedback for it to be useful. Reflection is required to integrate the information into the students’ schema networks. A meta-analysis of 40 studies showed results obtained from instructor feedback reflect the differences in how the feedback was used. If the students merely copied the correct answer, then the effect was not significant; however, if the student reflected on understanding why their answers were not correct, then substantial learning gains were made (Bangert-Drowns, Kulik, Kulik, & Morgan, 1991).

Clicker use does not necessarily promote learning. Clickers are used in classrooms for a variety of purposes – from taking attendance to promoting class discussion. The results of a mixed methods study suggest that how clickers are used determines the effect they have on learning (Fies & Marshall, 2008). In a classroom where the clickers were used solely for classroom management, taking attendance and pacing the class, students reported no added benefit to learning. Whereas in a classroom where clickers were used to increase student interaction by promoting group discussion, providing formative assessment feedback, and
scaffolding understanding, students reported positively on their use. The students in this interactive class reported benefits resulting from understanding what they did not know and knowing where they stood in the class. However some students reported that it was the small group discussion resulting from the clicker use that encouraged them to work harder toward deeper understanding (Fies & Marshall, 2008).

Another study that used clickers specifically as a means of feedback to questions asked in class found that the use of clickers did not have a significant impact on student performance (D. M. Bunce, VandenPlas, & Havanki, 2006). The students’ reflection on their answers and understanding why they were incorrect is critical to the clicker’s learning value. If the students are not given time to, or choose not to reflect, they miss a chance to make connections between new concepts and those already in their cognitive network. Without reflection learning gains may not be obvious (D. M. Bunce et al., 2006).

The parallel relationship of student participation in the learning environment and students’ schema development is diagramed in Figure 6. Moving the environment from teacher-centered to student-centered can help students’ schema development (Davis & Linn, 2000; Novak, 2002). Teaching to impart information may encourage students to memorize whereas an active student-centered environment may encourage students to think critically, construct their own knowledge, and reflect on their thinking (Sadlo & Richardson, 2003; Wilson & Fowler, 2005).
Learning Approach

Introduction

Novak and Gowin (1984) found that dramatic changes in learning environment away from rote learning to meaningful learning are met with resentment by 5 to 20 percent of students. An additional subgroup group of 5 to 20 percent will appreciate that the instruction helps them accomplish the type of learning they desire. Most students respond negatively at first, but change their minds after some experience with the new instruction. This experience results in new confidence in students’ learning skills (Novak & Gowin, 1984). The initial student
dissatisfaction may be due to unfamiliar demands for deeper thinking and the individual student’s predisposition for a particular approach to learning.

Meaningful learning is a continuum that requires commitment from the student (Novak, 2002). Figure 7 represents the two components that characterize meaningful learning. The first characteristic is the cognitive organization — richly elaborated and hierarchical schema. The second characteristic is the students’ commitment to conscious integration of concepts.

Figure 7. Characteristics of rote and meaningful learning, adapted from Novak (2002).

Some students believe that knowledge is facts so they take a surface approach to learning — using rote memorization and algorithmic problem solving — which leads to disconnected ideas. Other students believe knowledge is understanding so they take a deep approach to learning — seeking connections among concepts — which leads to an integrated network of ideas. How these two, meaningful learning and surface learning, are related will
help answer the practical question — do students learn by rote memory because of the way we teach or because of the students’ approach to learning?

According to Bruner (1966) students’ willingness to persist in a difficult subject, such as organic chemistry, is strongly affected by whether their approach to learning is “performance oriented” or “learning oriented.” Students who do not understand the developmental nature of learning, want to look smart and fear making mistakes (Dweck, 1989). Students who value learning appreciate new challenges whereas those that are performance oriented will not risk making errors, which interferes with their learning (Bransford et al., 2000). This reluctance to take risk for fear of making mistakes can prevent students from learning meaningfully by keeping them in a rote learning mode.

How does students’ belief of “what knowledge is” affect how they study? Many of the published studies on students’ approaches to learning originates with Marton and Säljö’s (1976) research. Säljö interviewed 90 individuals of varying age and education to find what “learning” meant to them. He categorized his findings into five different personal concepts of learning: (a) an increase of knowledge, (b) memorizing, (c) acquisition of facts or procedures, (d) abstraction of meaning, and (e) interpreting to understand reality (Säljö, 1979).

Marton and Säljö qualitatively evaluated how individuals read prose and, consistent with Ausubel’s findings, found that some read for meaning by relating the text to their prior knowledge and evaluating what they read with a critical eye. Others simply read for simple recall focusing on memorizing verbatim passages of text. In their study Marton and Säljö established a positive, qualitative correlation between a deep approach to learning and better learning outcomes, as compared to a surface approach to learning (Marton & Säljö, 1976).
Entwistle and Ramsden (1983), building on Marton and Säljö’s work, developed a self reported questionnaire, the Approaches to Study Inventory (ASI), to measure the degree to which a student’s strategy was focused on developing deep meaning versus acquiring superficial facts (Entwistle & Ramsden, 1983). Biggs (1987) developed a second inventory that was very similar to Entwistle’s (Biggs, 1987). Since then both surveys have been modified for specific research purposes and have been used to measure changes in student study strategies (Biggs, 1987; Edmonson, 1989; Richardson, 2005; Speth, Namuth, & Lee, 2007). The most recent form of this survey, the Approaches and Study Skills Inventory for Students (ASSIST), was modified by Entwistle to include a new strategic approach, a strategy used by the achievement-driven student. The strategic approach focuses on accomplishment resulting in attention to learning goals and organized studying on the part of the student (Entwistle, Tait, & McCune, 2000). These instruments, along with interviews, and other qualitative methods have been used to measure the effects of variables, such as pedagogy, on students' learning approaches that are discussed later in a separate section.

The three learning approaches addressed in this study: deep approach, strategic approach, and surface approach are based on the ASSIST survey. Deep learners are student who believe learning is a transformative experience and have an intrinsic interest in the subject. Surface learners are students who view learning as reproducing factual knowledge and are focused on completing tasks rather than understanding concepts. Strategic learners are achievement motivated and focus on faculty expectations and their grade performance (Wilson & Fowler, 2005).
Relationship of Student Learning Approach to Achievement and Concept Integration

Psychologists describe meaningful learning as integrating concepts into a hierarchal network of related concepts and propositions (Novak & Gowin, 1984). How students perceive “knowledge” influences their commitment to learning meaningfully. If students see knowledge as facts, they will likely use rote memorization for “learning”. However, if students see knowledge as understanding, they are likely to learn meaningfully by developing an extensive network of schema. Figure 8 shows the relationship of students’ views of learning and the related cognitive organization.

![Diagram showing the relationship of learning approach and schema development](image)

Figure 8. Relationship of learning approach and schema development

Variables that may Affect Student Learning Approach

In concordance with Marton and Säljö’s findings, Bretz (2005) stated that “student preferences are a direct extension of what the student believes it means ‘to know’ something”
Entwistle and Ramsden (1983) believed that since both the deep and strategic approaches are dependent on intrinsic motivation, and surface learning is driven by fear of failure, students prefer a particular approach based on their motivation, but students can modify their approach to the specific learning environment. Other researchers have also found that students have a preferred approach that can be modified to some extent by their environment (Chin & Brown, 2000; Kember, Charlesworth, Davies, McKay, & Stott, 1997; Laurillard, 1979). One study suggests that students’ learning approaches are very malleable (Laurillard, 1979). The major conclusion from the study is that students’ styles and strategies of learning are context-dependent: rather than applying to individual students, dichotomized descriptions of learning are more readily applicable to students in particular learning situations.

If students’ learning approaches are malleable, what variables can effect a change to a deeper approach? Students’ learning approaches have been studied with different variables: teaching methods, type of assessment, workload, discipline content, culture and student cognitive development (Richardson, 2005).

Effects of Learning Environment on Student Learning Approach

The learning environment in a classroom may affect students’ learning approach. Kember and Gow (1994) saw a parallel relationship of students’ learning approach and the degree of students’ participation in classroom learning. Just as students’ learning approach is based on what “learning” means to them, instructors’ choice of pedagogy is often based on what it means it means to them to “teach”.

Figure 9 is a diagram of the relationship between learning environment and students’ learning approach. If the instructor views teaching as simply transferring
information to students, then students may see this as a one-way process of receiving knowledge as facts, and facts can be memorized. Since theory has proposed that knowledge is constructed actively by the learner, this teaching philosophy may discourage a deep approach to learning. A teaching pedagogy that is designed to encourage students’ active participation and to facilitate understanding may foster a deeper learning approach in the students (Kember & Gow, 1994).

Figure 9. The relationship of pedagogy and learning approach, adapted from Entwistle, Skinner, Entwistle and Orr (2000).

The effects of pedagogy on learning approach have been studied, with mixed results. Some studies have found changes in learning approach with teaching method (Sadlo & Richardson, 2003). Other researchers have found that teaching interventions have been ineffective in changing learning strategies from surface to deep (Donn, 1990; Kember et al., 1997).
Why haven’t studies found a larger effect of learning interventions on student study approaches? There are several variables that influence the effect of learning intervention on students’ learning approaches. Some researchers think that student attitude is hard to change.

The lack of change “may be partly understood in terms of the persistence of existing attitudes and habits, the nature of students’ goals, the level of marks awarded, and the extent to which learning development is represented as an explicit goal by staff” (McCune & Entwistle, 2000, p. 15). When students reach the college level, years of previous science classes which emphasized rote learning and algorithmic approaches have been engrained into their learning style. It is difficult for students to make the switch from algorithmic approaches to conceptual learning (Novak, 2002).

*Students’ Cognitive Development and Learning Approach*

Cognitive development may be related to students’ choice of learning strategy. In a study using Perry’s theory of ethical and intellectual development to measure the cognitive development of students, the researchers found that students’ cognitive development was correlated with their learning approach. A dichotomist (dualist) view positively correlated with a surface approach, but negatively and significantly correlated with a deep approach. Cognitive relativism was negatively correlated with surface approach, and positively correlated with a deep approach (Zhang & Watkins, 2001). Therefore students who prefer a surface approach may do so because they are concrete learners. They may not be able to adopt a deep approach until they move to formal thinking. Eley (1992) found that students’ responses to the metacognitive focus and independent learning questions in his survey were strongly correlated
with deeper learning approaches, suggesting if teaching is focused on developing strong cognitive processes in students, a deeper student approach to learning will follow (Eley, 1992).

Effects of Workload on Learning Approach

Trigwell and Prosser (1991) found that a perceived heavy workload is related to a surface approach. The teaching methods (in the experiment) “pushed students towards surface approaches of learning to cope with the high workload requirement. High workloads are found in content intensive courses, such as organic chemistry, in which the focus is often on the transfer of large amounts of information. Transfer of information as the primary teaching goal is associated with surface learning (Gow & Kember, 1993; Kember & Gow, 1994). Superficial coverage of many topics in a discipline should be replaced with in-depth coverage of fewer topics to allow key concepts to be understood (Bransford et al., 2000). Meaningful learning takes more time than rote learning, so more time must be provided.

Studies of Learning Approach and Student Outcomes

The few studies that try to compare students’ learning approach with students’ “outcomes” are not easily compared since the studies used different definitions of outcome – some qualitative and some quantitative. For example, one study measured students’ outcome based their responses to interview questions concerning the course in general and not a measure of mastery of the course content (Trigwell & Prosser, 1991). The study found a negative correlation of a surface approach to learning and student outcome (as measured qualitatively in the interviews), but no correlation between a deep approach and outcome.

Ramsden (1992) found that understanding is less positively related to a deep approach than it is negatively related to a surface approach. He used qualitative outcome measures
because he thought quantitative measures, such as grades, were a less valid and reliable measure. He argued that the relationship between learning approach and quantitative measures of outcome is much weaker than between learning approaches and qualitative measures of learning outcomes, because of lower validity of the quantitative measures.

A later study by Scouller and Prosser (1994) resolved some of this debate over quantitative and qualitative measures by comparing assessment using multiple choice questions with assessment of student essays. Using the essays as a quantitative measurement of outcome, the study found a positive relationship between deep learning approach and students’ outcome.

*Relationships between Learning Approach and Assessment Results*

Because assessment may impact how students approach learning it is difficult to compare studies which use different assessment measures because the measurement may influence the variable. When an innovation fails to move students towards deeper conceptual understanding, the real cause may lie with the assessment used. Grades are student “pay”. It is possible that an intervention designed to deepen students’ learning may fail because the assessment method encourages surface learning. This was the conclusion in more than one study (Donn, 1990; Scouller, 1998). Assessment is so important that “the teacher’s choice about what to assess and how to assess is actually more influential upon student learning strategies than the students’ own preferences” (Bretz, 2005).

Objective tests may encourage surface learning, whereas assessments that ask the students to apply, explain, or interpret may encourage deeper, meaningful learning. Multiple-choice exams are often used in large classes because of the increased grading load that free
response exams entail. Some multiple-choice questions do require critical thinking, but students need only identify an already formulated answer in such questions. In composing an answer to a free response question students must synthesize their own argument that means using analytical and critical thinking skills indicative of a deeper approach. Students must formulate and communicate a reasoned answer and have control over the presentation of their understanding of the material (Scouller, 1998).

In her study comparing the multiple choice and essay assessments with student learning approaches, Scouller found a distinct relationship between type of assessment (multiple choice or essay), student learning approach (deep or surface), and student score on the assessment. On multiple-choice tests students were more likely to use a surface learning approach and to view the multiple choice test as requiring lower level (fact based) cognitive functioning. On these multiple choice tests students with a deep approach scored lower than those with a surface approach. However on essay assignments, students tended to adopt a deeper approach, and view the assessment as requiring higher levels of cognitive functioning. On these essay assignments students with a deep approach scored higher than those with a surface approach (Scouller, 1998).

When students enter a class that emphasizes deep learning and it is new to them, it takes time for the students to adjust. Initially, student scores on objective achievement measures, such as multiple choice tests, may be lower in a class emphasizing meaningful learning than in a class where surface learning occurs. After an adjustment period, which may be as long as 8 weeks or more, students are able to use concepts learned to answer multiple choice and short answer questions and objective scores will improve. However, students in
classes that emphasize meaningful learning score significantly better on problem solving tests than students in other classes at the beginning of the semester and they continue to improve with time (Novak & Gowin, 1984).

Students develop an approach to learning based on what they believe knowledge is – if knowledge is facts then they use rote memorization, and if knowledge is understanding they seek to integrate new ideas with their existing knowledge (Edmondson, 1989). There view of knowledge may be influenced by the learning environment and the form of assessment. Figure 8 shown previously diagrams the relationship of students’ views on knowledge and their schema development.

Summary

The fields of neurobiology and developmental, cognitive, and educational psychology have advanced similar theories of meaningful learning. These theories propose: (a) meaningful learning occurs through concept integration rather than rote memorization (Ausubel, 1963; Piaget, 1977a), (b) concept integration begins with concept recognition in isolation and progresses as it is linked to existing concepts and integrated into the schema network (Piaget, 1977a; Vygotsky, 1978), (c) experts have a more extensive integration of concepts in a high quality, well organized, hierarchic network (Chi et al., 1988; Lawson et al., 1989), and (d) the higher generality understood, the deeper the learning (Ausubel, 1963).

Achievement, defined as problem solving, is the commonly accepted criteria for students’ success, but students can achieve it without conceptual understanding (Bhattacharyya & Bodner, 2005; D. M. Bunce et al., 1991; Gabel et al., 1984; Herron & Greenbowe, 1986; Nurrenbern & Pickering, 1987). Achievement represents progress through
Learning Development Stages I and II; concept integration differs from achievement in that students are able to link related concepts, explain and apply them to novel situations that build more extensive schema networks that are characteristic of Learning Developmental Stages III and IV (Liu et al., 2008). To learn meaningfully, students must: (a) have a foundation of factual knowledge, (b) understand ideas in the context of a conceptual framework, and (c) organize concepts in ways that facilitate retrieval and application (Bransford et al., 2000).

The learning environment can affect the depth of student learning. How materials are organized and presented to students may have an impact on students’ conceptual understanding, but often the materials are organized the way experts think, making it difficult for a novice to fully comprehend (Lawson, 2003). Moving the environment from teacher-centered to student-centered can help students’ schema development (Davis & Linn, 2000; Novak, 2002). Teaching as imparting information may encourage students’ to memorize whereas an active student-centered environment can encourage students to think critically, construct their own knowledge, and reflect on their thinking (Sadlo & Richardson, 2003; Wilson & Fowler, 2005). Gagné and Brown (1961) suggested that scaffolding, in terms of probing questions, can give students the needed guidance to learn how to think critically. Use of the Learning Cycle, which imitates the way the brain learns and the scientific thought process, can help students integrate concepts into their existing schema by following a cycle of exploration, concept invention, and concept expansion (Lawson, 2006). In-class discussions can reveal students’ thinking to themselves allowing them to fill gaps in their schema (Bransford et al., 2000). Technology used in large classes, such as clickers, can provide the feedback needed from students to enable the instructor to provide timely clarifications (Fies & Marshall, 2008).
However, students must be given the opportunity for, and choose, thoughtful reflection to make connections between the new concepts with their existing schema (D. M. Bunce et al., 2006). The relationships of learning environment, learning approach, and schema development are diagrammed in Figure 10.

Figure 10. Relationships among learning environment, learning approach and meaningful learning.
CHAPTER III

METHODOLOGY

Introduction

The research topic for this study is the relationship of student learning approach – deep, strategic, or surface— with achievement and concept integration. Thus an understanding of each is important to understanding their relationship, if any.

The literature reports that meaningful learning occurs through concept integration rather than rote memorization. The concept cannot be integrated until it is first recognized in isolation (Ausubel, 1963). Meaningful learning progresses as the new concept is linked to existing concepts and integrated into the schema network (Ausubel, 1968). The more extensive the integration of the concept into the network and the higher generality that is understood, then the deeper the learning (Ausubel, 1963; Chi et al., 1988; Vygotsky, 1978). In addition Trigwell and Prosser (1991) have demonstrated general relationships between a student’s learning approach (deep, strategic, or surface), grades, and qualitative measures of learning (Trigwell & Prosser, 1991).

Before investigating any relationship of these two sets of variables, it is necessary to study them separately. The first two research questions address each of these two sets of variables separately and the third investigates a possible relationship between them.

This chapter describes the methodology used in the investigation – the sample population, environment and research design. The development of the study’s instruments and their validity and reliability are discussed along with methods used to construct and score assessment questions to differentiate between achievement and concept integration.
Research Questions and Null Hypotheses

Research Question 1

What is the effect of time within a topic and across related topics on student achievement and concept integration when using a guided inquiry approach in a large first semester organic chemistry class environment?

NULL HYPOTHESIS 1: Students who complete one semester of guided inquiry in a large first semester organic chemistry class will show no significant differences in achievement or concept integration with time either within a topic or between related topics.

Research Question 2

Are the students’ preferred learning approaches affected by a semester-long experience in a guided inquiry first semester organic chemistry class?

NULL HYPOTHESIS 2: Students who complete one semester of guided inquiry in a large first semester organic chemistry class will show no significant differences in learning approach from the beginning to the end of the semester as measured by the ASSIST survey.

Research Question 3

What is the relationship between students’ preferred learning approach (as measured by the ASSIST survey) and their concept integration and achievement in a large first semester organic chemistry class?

NULL HYPOTHESIS 3: There is no correlation between learning approach and either concept integration or achievement for students who complete one semester of guided inquiry in a large first semester organic chemistry class.
Methodology Overview

Three related topics are used to investigate meaningful learning in first semester organic chemistry – acid/ base, nucleophilic substitution, and electrophilic addition reactions and their mechanistic pathways. These topics are selected for this investigation for two reasons: (a) in a recent study the two most difficult topics named by organic educators for student learning were reaction mechanisms and acid/ base chemistry (Duis, 2008), and (b) the concepts in these three topics are related at a higher generality – electron density of the chemical species, electron pair energies and their effects on chemical reactions.

Research Question 1 is investigated using data collected from the three topics – acid base chemistry, nucleophilic substitution, and electrophilic addition – to study achievement and concept integration within and across these topics. The “within topic” measurements of achievement and concept integration are made as the student progresses through a specific topic, such as electrophilic addition. The “across topics” measures the integration of concepts among the three topics.

Each of the three topics is taught using two in-class guided inquiry activities scheduled for two periods for a total of six class periods. Occasionally the topic’s second activity extended to a third class period. Immediate achievement and concept integration are measured using electronic polling devices or “clickers” during each of the six activities and again approximately one week after the completion of the second activity worksheet. All other achievement and concept development measurements are made by evaluating the three topics on both the three hourly examinations and the final examination.
Table 2 provides a summary of measurements which are explained further in the tools' section of this chapter. The across topic achievement and concept integration are measured using a written, multi-part free response question on the final exam linking all three topics. The within topic achievement and concept integration for each of the three topics are measured as follows:

(1) The immediate achievement and concept integration for the first activity on each topic are measured using two linked questions administered via the student classroom response system (clickers).

(2) During the next activity on the topic, a second measurement of immediate achievement and concept integration is implemented using a different two part linked clicker question. This question measures integration of the second activity’s achievement and concept integration and its integration with the first activity’s concepts. The answer and results of this question is not shown or discussed with the students.

(3) Approximately one week after the second measurement, time delayed achievement and concept integration measurements are made using the same two part clicker question from the second activity.

(4) The intermediate achievement and integration of concepts for the whole topic are measured using a written, multi-part, free response question on the hourly exam covering that topic.
Table 2
Summary of Measurement Occasions

<table>
<thead>
<tr>
<th>Topic</th>
<th>Occasion</th>
<th>Assessment</th>
<th>Format</th>
<th>Time Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid / Base</td>
<td>1</td>
<td>1st Activity</td>
<td>Clicker</td>
<td>Immediate</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2nd Activity</td>
<td>Clicker</td>
<td>Immediate</td>
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<tr>
<td></td>
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<td></td>
<td>4</td>
<td>End of Topic</td>
<td>Hourly Exam</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Nucleophilic Substitution</td>
<td>1</td>
<td>1st Activity</td>
<td>Clicker</td>
<td>Immediate</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2nd Activity</td>
<td>Clicker</td>
<td>Immediate</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Post 2nd Activity</td>
<td>Clicker</td>
<td>Delayed</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>End of Topic</td>
<td>Hourly Exam</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Electrophilic Addition</td>
<td>1</td>
<td>1st Activity</td>
<td>Clicker</td>
<td>Immediate</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2nd Activity</td>
<td>Clicker</td>
<td>Immediate</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Post 2nd Activity</td>
<td>Clicker</td>
<td>Delayed</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>End of Topic</td>
<td>Hourly Exam</td>
<td>Intermediate</td>
</tr>
<tr>
<td>Final Exam</td>
<td></td>
<td>Across Topics</td>
<td>Final Exam</td>
<td>Long Delay</td>
</tr>
</tbody>
</table>

Research Question 2 is investigated using the Approaches and Study Skills Inventory for Students (ASSIST) survey instrument. Students complete this self-report survey at both the beginning and the end of the semester. The average student scores for deep learning approach,
strategic learning approach, and surface learning approach are calculated from the pre- and post-surveys.

Research Question 3 uses the data from the first two questions. From Research Question 1 the average of the final exam question and the three hourly exam questions scores are used as measures of achievement and concept integration. Individual student scores from the pre-semester ASSIST survey are used to address Research Question 2 to classify the three types of learning approaches.

Sample

The participants chosen for this investigation are a convenience sample of students enrolled in one section of sophomore level Organic Chemistry I offered at Virginia Commonwealth University (VCU) in Richmond, Virginia in the fall semester 2008. VCU is a large, urban, research university with approximately 33,000 students. The student body is diverse in ethnicity, age, and ability. Eighty percent of students commute and 30% attend class part time. The average VCU student’s SAT score is 1103. In recent years the College of Humanities and Sciences has been experiencing high withdrawal rates – a typical DFW (grades of D and F and withdrawals) rate is 25-44% in introductory and general chemistry classes and 32-60% in general biology classes (Ruder & Hunnicut, 2008). In organic chemistry the five year average for the DFW rate is 42%. Although the DFW rate has increased, the SAT scores have not dropped so the higher DFW rate may be due in part to the university’s rapid growth and the resulting crowded classes.

The VCU organic chemistry course is designed for science or pre-professional health majors who have successfully completed the freshman level general chemistry course for
science majors with a grade of C or better. The course section in this study is taught using the POGIL method whereas other two sections of the same course are taught in an expository lecture format. Students enrolled in this section of the course are asked to read and complete a consent statement for this investigation (Appendix A). Of the 250 students enrolled, only 166 were included in the study for the following reasons: 35 declined to participate, 27 did not take the final exam and 43 were repeating the course.

Teaching Team

Instructor

The instructor has 20 years experience teaching organic chemistry, 15 years teaching using a lecture format and the last 5 years using the process oriented guided inquiry learning (POGIL) method. She is also a curriculum author and an experienced researcher in synthetic organic chemistry. The POGIL materials developed for the organic chemistry course under investigation and the adaptations made to the POGIL method for a large class were designed by the instructor.

Teaching Assistants

In addition to the instructor, six undergraduate teaching assistants (TAs) were trained to act as facilitators for the classroom activities. The TAs have all completed the two semester organic course sequence; however, five of the six TAs took the course under another instructor in a lecture format. Several of the TAs had experienced POGIL either in general chemistry or physical chemistry courses. Each week during the semester the TAs met with the instructor to prepare for the coming week’s class. During the first meeting the TAs were introduced to the POGIL method, and what was expected of classroom facilitators. During subsequent TA
meetings, they reviewed the class activities and discussed how to handle potential student questions and group interactions. The TAs’ responsibilities included circulating through the classroom to coach students through the activity, holding a weekly study section (optional for students) and managing the distribution of student papers in folders handed out and picked up from each group. Each pair of TAs conducted one study session per week for a total of three weekly study sessions each week.

Environment

Physical

This course is taught in a large lecture hall of 300 fixed seats using POGIL modified for large classes (Ruder & Hunnicut, 2008). All participants in this study are students in the same class section that meet for 90 minutes each on Tuesday and Thursday morning for 29 class meetings over 15 weeks during the semester. Three class meetings are used for hourly examinations. There is no recitation section; however, students may attend an optional help session once per week led by their undergraduate peer-teaching assistants or meet with their instructor during her office hours. It is estimated that no more than 12% of the class attended these help sessions on a regular basis; however, attendance at help sessions is estimated to have increased to 15% or higher the day before each hourly exam.

Academic

POGIL is an active teaching/learning pedagogy that utilizes the Learning Cycle. Students work during class time in self-managed teams consisting of three to five students. In these groups they work together on guided-inquiry activities that are specifically designed around the Learning Cycle. The in-class activities are divided into sections, in which each section begins
with a model and follows a pattern of exploration, concept formation, and application. The model may be a partial mechanism, data from an experiment, or other type of information.

Students work in their groups of four to explore the model, answer critical thinking questions about the model, discuss and reach a consensus on each section of the activity. In the process of working as a team on critical thinking questions, students also develop key process skills: information processing, critical thinking, problem solving, teamwork, communication, and metacognition. Of these, information processing, critical thinking and metacognition are key processes used in schema development.

The students are assigned rotating responsibilities for their groups. The group’s scribe records the group’s consensus answers, the presenter is the spokesperson for the group, the reflector observes and comments on the group’s effectiveness and learning outcomes, while the manager encourages participation and organizes the group’s activities.

The instructor facilitates learning by circulating through the classroom, observing and interacting with groups, and inducing students to arrive at their own conclusions rather than providing answers directly or transmitting information. After each model, the spokesperson for the group “reports out” on the group’s findings and underlying reasoning to the whole class. The instructor clarifies any misunderstandings and may address the class as a whole. At the end of the class each group’s “reflector” may give the instructor a written summary of the group’s reflection on learning outcomes. This may include concepts they learned and concepts that are still unclear to the group (Hanson, 2008; Moog & Farrell, 1997).

In the class under study, modifications to the POGIL method were made to adapt this method to a large class environment. The modifications used were student clickers, an
instructor tablet PC, PowerPoint™ (PPT) and TAs. The clickers are used for student “reporting out” after each model, the tablet PC and PPT enable the instructor to interact with the students, and the TAs provide facilitation to student groups.

The instructor wrote the in-class POGIL activities then posted them on the Blackboard Website for students prior to class. The instructor used PPT presentation software to pace the class and pose “clicker” questions to the class. The group’s presenter answered the questions for the group using the clicker. The tablet PC is used with PPT to review the activity once it is completed by the students in class and to give further clarification as needed. After class this “completed” PPT was posted on the Blackboard Website to provide students access for review.

The instructor trained the TAs how to facilitate the in-class activities. The TAs were responsible for collecting and distributing materials to student groups, circulating in the room assisting groups during class, and conducting help sessions each week.

The students worked in a self selected group to work on in-class activities over the course of the semester. Students were required to print these class activities prior to coming to class. Individually assigned CPS™ Electronic Response System input pads by eInstruction (clickers) were used so that students could respond to in-class questions that followed each model of an activity. The results from the clicker questions allowed the instructor to receive survey feedback from the class on how well they understood a particular topic. From this information the instructor could determine whether a whole class discussion or mini-lecture on the topic was necessary. Participation in these group clicker questions contributed 5% to the student’s overall grade. In addition, individual quizzes were given during class and are worth 10% of the final grade. These quizzes consisted of 12 individual “clicker” questions and five
short written assessments during the semester. Outside of class the students were required to read the subject material from a widely used textbook (Wade, 2005) and they completed electronic homework using the software program Achieving Chemistry Excellence (ACE, Prentice Hall). The electronic homework consisted of free response questions that require the students to draw structural formulas that were graded. Students were permitted four attempts at the same problem and the electronic homework contributed to 5% of their grade. The remaining 80% of the course grade was through individual assessments – three hourly examinations contributed 50% and the final examination 30%. A schedule of the class topics and activities is given in Appendix B.

Research Design

Introduction

Achievement and concept integration may be related to students’ individual learning approach. They may be influenced by using the guided inquiry activities and by working in groups in the classroom. Initially, learning approaches and concept integration/achievement are considered separately and then the relationship between them is studied. The first research question asks how continued exposure to the concepts via the guided inquiry environment affects achievement and concept integration. The second question asks if the guided inquiry environment impacts students’ learning approach. The third question asks if there is a correlation among learning approach and achievement and concept integration.

The first research question may lead to an understanding of how meaningful learning occurs in organic chemistry. Meaningful learning of the effects of electron charge distribution and electron pair energies on chemical reactivity cannot occur without integrating the concepts
of positive and negative charges, acids and bases, and nucleophiles and electrophiles. Each of these concepts must be integrated in the schema of electron charge distribution, electron pair energies, and chemical reactivity. This occurs in developmental stages. These developmental stages, in the form of achievement and concept integration, are measured by student answers to in-class objective clicker questions and free response questions on hourly examinations that provide evidence of linkage among these related concepts.

The second research question may lead to an understanding of how malleable student learning approach is. This question investigates the effect of classroom emphasis on deep learning through the use of guided inquiry activities on student learning approach. Effects on student learning approach are measured using a self-reported survey (ASSIST) administered both at the beginning and end of the course.

The third question studies the correlation of these two sets of variables – achievement and concept integration with learning approach. Correlation is calculated using data collected to answer the first two research questions.

Developmental Stages

Learning occurs through developmental stages as shown in Table 3. Learning is based on existing knowledge, Stage I, and progresses to Stage II in which the student learns the concept identity in isolation. In Stage II the student can name the concept and recognize an example, such as “the hydroxide ion, \( \text{OH}^- \), can act as a base”. They may be able to successfully complete an achievement problem, but sometimes a common misunderstanding will lead to incorrect answers because the concept integration is incomplete. For example if the students’ concept of bases is too narrow, it may not include neutral species, so that students may not be able to
recognize water acting as a base in a reaction because they are looking for a negative formal charge. In Stage II the student can demonstrate achievement by using an algorithm and pattern matching to solve problems, but the concept may not be connected into related schema. Achievement is defined as algorithmic learning in this study so the student may not be able to provide conceptual explanations for their achievement.

Table 3

*Developmental Stages of Learning, adapted from (Briggs et al., 2006)*

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Demonstrates expected prerequisite knowledge from prior course or prior topic</td>
</tr>
<tr>
<td>II</td>
<td>Correct answer without explanation or common misconception that leads to an incorrect answer</td>
</tr>
<tr>
<td>III</td>
<td>Correct answer, explanation and application to new situation, but mistake in subtle, complex or more advanced aspect of problem</td>
</tr>
<tr>
<td>IV</td>
<td>Full Integration of concepts including understanding of subtle, complex or more advanced aspects</td>
</tr>
</tbody>
</table>

As students progress to Stage III they recognize basic connections to other related concepts and can generalize to a higher level. There are three important differences in Stage III from Stage II: (a) problem solving is based on concepts rather than on pattern recognition or an algorithm, (b) the student not only can apply the concept but can explain the underlying reasoning, and (c) the concept can be applied to a problem in a new situation. However, in Stage III the student may miss an advanced or subtle aspect of the problem because the
concept is only partially integrated in their schema. For example, the student may be able to recognize that the same species can act as a base or nucleophile, and explain the underlying differences, but cannot explain the effects of polarizability or solvent on a nucleophile’s strength. By Stage IV the student has advanced to complete understanding through full integration of the interrelated concepts and is able to explain more advanced concepts such as solvent effects and hard and soft bases. Stage V represents expert knowledge that is not measured in this study.

Achievement

Achievement, as used in this study, is the ability to solve problems by applying an algorithm or pattern recognition. Achievement is measured in this study with a score of 0-4 that describes the characteristics of the answer the student provided as shown in Table 4.

Table 4

<table>
<thead>
<tr>
<th>Characteristics of student response</th>
<th>Achievement Score</th>
<th>Developmental Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>No response</td>
<td>0</td>
<td>I</td>
</tr>
<tr>
<td>Reflects only prerequisite knowledge</td>
<td>1</td>
<td>I</td>
</tr>
<tr>
<td>Wrong answer due to common misunderstanding</td>
<td>2</td>
<td>I</td>
</tr>
<tr>
<td>Basically correct answer but incorrect subtle or advanced concepts</td>
<td>3</td>
<td>II</td>
</tr>
<tr>
<td>Completely correct answer</td>
<td>4</td>
<td>II</td>
</tr>
</tbody>
</table>
The student matches the characteristics of a problem to a learned mental template and generates a matched output. A typical achievement question asks the students to predict the products of a reaction. Students may be able to answer this question by using a template that says alcohols and primary alkyl halides react to form ethers, and then match output for the specific alcohol and alkyl halide named in the problem. The algorithm directs the student to: remove the halide ion from the alkyl halide, remove the proton from the alcohol and bond the remaining pieces through the oxygen. This is an example of achievement with surface pattern recognition that represents Developmental Stages I and II only.

*Concept Integration*

Concept integration only occurs in Developmental Stages III and IV because until that point the student has not grasped the new concept’s identity. Concept integration is scored in this study as 0-4, that describe the student’s answer as shown in Table 5.

Concept integration is the connection of the new concept to an existing concept in the schema network. The more extensive the integration with other concepts, the better able the student is to move to a higher level of generalization. This is the hallmark of expert knowledge. Achievement and concept integration represent progress through different developmental stages. In the two initial development stages, Stage I and II, achievement is acquired through the ability to work problems using pattern recognition. At the end of Stage II the student can name and identify examples of the concept. This concept acquisition is still mainly that of a “stand alone” concept and is not integrated into the student’s schemata. It is not until Stage III that concept integration begins as the student makes connections first with other concepts and then with its position in the student’s schema. This integration only occurs at the higher
developmental levels as shown in Table 6. This progression is not linear. For multiple concepts these developmental stages can overlap and the student may be at different stages for different concepts within a topic.

Table 5

*Relationship of Concept Integration to Developmental Stages, adapted from Liu et al. (2008)*

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Concept Integration Score</th>
<th>Developmental Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incorrect answer</td>
<td>0</td>
<td>I</td>
</tr>
<tr>
<td>Names concept but cannot explain or link it to a related concept</td>
<td>1</td>
<td>II</td>
</tr>
<tr>
<td>Relevant connection of concept to another concept – but with partial explanation</td>
<td>2</td>
<td>III</td>
</tr>
<tr>
<td>Relevant connection of concept to one other concept with full elaboration</td>
<td>3</td>
<td>III</td>
</tr>
<tr>
<td>Relevant connection of concept to more than one other concept with full elaboration</td>
<td>4</td>
<td>IV</td>
</tr>
</tbody>
</table>

Table 6

*Relationship of Achievement and Concept Integration to Developmental Stages*

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Achievement Score</th>
<th>Concept Integration Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0, 1</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>2, 3, 4</td>
<td>1</td>
</tr>
<tr>
<td>III</td>
<td></td>
<td>2, 3</td>
</tr>
<tr>
<td>IV</td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>
Achievement is defined here as ability to solve problems using pattern recognition whereas concept integration is the demonstrated ability to link ideas and to apply them in situations not experienced before. Achievement and concept integration are related to the student’s developmental learning stage. To develop valid instruments that measure achievement and concept integration, and also differentiate between the two, a tool must be developed that describes the expected student understanding at each developmental stage for each individual in-class activity. The instructor’s objectives and the concepts for each activity are fitted into a developmental stage map called a construct map. The construct map reflects the instructor’s objectives and a common learning path that includes misunderstandings or disconnects between concepts often seen in students who are studying the concepts in the activity.

A sample construct map for an activity is shown in Table 7. The construct maps and their associated instructor-written activities are found in Appendices C and D, respectively. Each activity and its associated construct map were validated by two POGIL organic professors from different institutions to assure that the activity would prepare a student for the concepts described in the construct map. The two organic professors chosen for validation have a combined experience of more than twenty-five years teaching organic chemistry using POGIL and have authored several POGIL activities. The construct maps were used to write the assessment questions that differentiate among developmental stages and to measure achievement and concept integration.
Table 7

Sample Construct Map: $S_N1$

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Description</th>
<th>Constructs</th>
</tr>
</thead>
</table>
| I                   | Expected Prior Knowledge | Carbocation structure and hybridization affects shape and stability  
Knows what a substitution reaction is and can identify specific reactions  
Understands the concept of potential energy diagrams  
Knows in general that reaction rate depends on concentration of species |
| II                  | Common Misconception that results in wrong answer | Can predict the product of a substitution reaction and draw mechanism for $S_N1$ reaction but cannot explain what the arrows mean  
Can identify roles of reagents as nucleophiles and electrophiles but cannot differentiate strength between two nucleophiles or electrophiles  
Can identify species in energy diagram but cannot explain their energy differences |
| III                 | Basic understanding except for one new concept | Can draw complete mechanism and explain what the arrows represent  
Understands the stereochemistry of the reaction and the impact of the flat carbocation but cannot explain why product is not exactly 50/50 racemic mixture  
Can predict between competing mechanisms of $S_N1$ or $S_N2$ when given only 1 variable |
| IV                  | Full Integration of current topic | Predict between $S_N1$ or $S_N2$ mechanisms with multiple variables and explain  
Predict when rearrangement can occur and draw the rearranged product  
Understands and can explain stereochemistry of the planar intermediate such as solvent effects, relationship of rate and concentration of reagent,  
Can explain the relationship of rate to electrophile’s structure and nucleophilic strength |
Assessment Instruments

Differentiating between Achievement and Concept Integration

In this study achievement and concept integration are measured with a dual-purpose instrument using two-tier questions (Treagust, 1995). One tier is directed at measuring achievement while the second tier measures concept integration. One part of the question is a standard achievement question generally recognized as an expected learning outcome in a university organic chemistry course. The second part of the question measures concept integration by requiring students to provide their reasoning for the first question’s answer or relate concepts from previous topics. An example of this type of question is shown in Figure 11. All achievement and concept integration instruments in this study follow this pattern and each dual-purpose instrument provides two scores – one for achievement and one for concept integration. Both scores range from 0-4, but, as discussed earlier, they relate to different developmental stages of learning.

Question Formats

There are two different formats of the two-tiered questions used in this study. Because student answers are collected in different assessment environments, some immediately after the in-class activity and some later on the hourly exam, no single format would work for both.
The following reaction of an alcohol to an alkene is an E1 reaction. A proposed but incorrect mechanism is shown below; step 1 of the mechanism as drawn is unlikely.

**Overall Reaction**

[Chemical structure image]

**Proposed Mechanism**

[Chemical structure image]

**Concept Integration:**

(a) Explain why step 1 of the proposed mechanism is unlikely. *Relate as many concepts as are appropriate* (acid, base, nucleophile, electrophile, positive or negative charges, intermediates, lone pairs, etc.)

**Achievement:**

(b) Draw arrows to show electron movement for each step of the correct mechanism in the reaction below. (The atoms are numbered for the next question.)

[Chemical structure image]

**Concept Integration:**

(c) Using the atom numbers for reference, describe each step of the mechanism. Be sure to describe explicitly what happens with each arrow and the chemical basis for your reasoning.

*Figure 11.* Sample dual-purpose, multi-part, written free response question.
The answers to the hourly and final exam test questions are hand written by the students, and are comprised of multi-part free response questions as shown in Figure 12. These questions direct students to formulate their own answers using all the concepts they think are related.

The in-class post activity questions are collected electronically using the student class response system (clickers). An example of this type of question is shown in Figure 12.

**Achievement:**

The $S_{n2}$ transition state (ts) is drawn below. (The direction the transition state is written does NOT indicate the reactants or products in this case.)

**First number:** In the ts, which of the following would be the nucleophile?

1. Cl⁻
2. -OCH₃
3. -CH₃

**Second number:** In the ts, which of the following would be the leaving group?

4. Cl⁻
5. -OCH₃
6. -CH₃

**Concept Integration:**

Which explanation(s) support(s) that -OCH₃ is the nucleophile and Cl⁻ is the leaving group? Enter all numbers that are correct OR # 6 for “I don’t know why”.

1. The pKa for HCl (<0) is lower than CH₃OH (~16).
2. The lone pair on Cl⁻ is more stable than the lone pair on -OCH₃, so Cl⁻ is a lower energy product.
3. Both can be nucleophiles but -OCH₃ is a stronger base than Cl⁻.
4. The bond between C and -OCH₃ is stronger than the bond between C and Cl⁻.
5. CH₃OH and Cl⁻ are lower in energy than CH₃Cl and -OH
6. I don’t know why

*Figure 12. Sample dual-purpose two-tiered clicker question.*
The clicker question format differs from that of the test questions in that the student does not construct the answer but chooses from a selection of answers. The format is adapted from the Ordered Multiple Choice format (Briggs et al., 2006), and permits measurement of various levels of understanding based on the constructs for which the activity was designed. However, the “multiple answer “clicker questions in this study do give the student more choices and responsibility for formulating their answers than the typical multiple-choice format. Students were instructed to use their clickers to input a series of numbers indicating all the correct answer choices in the correct sequence. The strings of answers are used to determine students’ scores.

Construct validity for the free response exam questions and the in-class clicker questions were determined through peer-review by two experienced organic POGIL professors with extensive experience teaching this course. In order to insure that the questions tested the concepts in the in-class activity, the question review was performed at the same time the constructs and instructor written activities were reviewed. Modifications to the questions and activities were made based on the reviewer’s recommendations. The questions used can be found in Appendix E.

Construct validity for the free response exam questions and the in-class clicker questions were determined through peer-review by two experienced organic POGIL professors with extensive experience teaching this course. In order to insure that the questions tested the concepts in the in-class activity, the question review was performed at the same time the constructs and instructor written activities were reviewed. Modifications to the questions and
activities were made based on the reviewer’s recommendations. (The questions which were used appear in Appendix E.)

**Grading Rubrics**

The scoring of all measures was based on the construct map(s) for that activity or, in the case of an exam question, all the activities in that topic. The rubric used to grade achievement for both the two-tiered multiple answer clicker questions and the free response exam questions is shown previously in Table 4. Achievement scores, adapted from (Briggs et al., 2006) in the Research Design/Achievement section. Written exam questions were graded manually using the rubric. The two-tiered multiple answer clicker questions were graded in SPSS by assigning achievement scores to the appropriate numerical answers. For example, in the clicker question in Figure 12, a score of 4 would be assigned to the correct answer “24” because, for the reaction’s equilibrium position to favor the products, chloride must be the leaving group and methoxide the nucleophile. In the same question, a score of 2 was assigned to an answer of “34” because it demonstrates the common confusion over which bond to oxygen breaks. A score of 0 would be assigned to the answer “36” because it does not demonstrate any achievement. The students' answer strings were graded and assigned scores of 1-4 within SPSS.

The rubric used to grade concept integration for the two-tiered clicker questions is shown previously in Table 5: Concept Integration scores, adapted from (Liu et al., 2008) in the Research Design/Concept Integration section. Again, numerical combinations of the student answers are assigned scores in SPSS based on the rubric. The more correct concepts the student identified, the higher the concept integration score. The written free response exam questions are graded manually using a flow chart as a guide. Figure 13 shows the general
format for the flow chart used in this study to differentiate a correct answer further into four levels of integration (Liu et al., 2008).

\[ \text{ACHIEVEMENT} \]
\[ \text{Does the answer address the question?} \]
\[ \text{Is the answer scientifically valid?} \]
\[ \text{Yes} \]
\[ \text{CONCEPT INTEGRATION} \]
\[ \text{Are concepts connected?} \]
\[ \text{Is the connection valid?} \]
\[ \text{Yes} \]
\[ \text{Is the connection elaborated fully?} \]
\[ \text{Yes} \]
\[ \text{Number of fully linked concepts} \]
\[ \text{One} \]
\[ \text{More than one} \]
\[ \text{Off Task} \]
\[ \text{No Link} \]
\[ \text{Partial Link} \]
\[ \text{Full Link} \]
\[ \text{Complex Link} \]
\[ \text{Score} = 0 \]
\[ \text{Score} = 1 \]
\[ \text{Score} = 2 \]
\[ \text{Score} = 3 \]
\[ \text{Score} = 4 \]

*Figure 13. Scoring flow chart for free response concept integration questions, adapted from Liu et al. (2008).*

An example of the grading process can be demonstrated using the free response final exam question previously shown in Figure 11. For part a, a score of 1 would be assigned to a student's answer "hydroxide ion is a poor leaving group". This is a correct (and common) answer but does not demonstrate an understanding of the several concepts shown in this question. A score of 3 would be assigned to an answer "if the hydroxide ion were the leaving group it would neutralize the acid catalyst. Cations and anions are not likely to exist in the same
solution.” A score of 4 would be assigned to a discussion that related all of the concepts or expressed at a higher general level, such as the relative energies of the electron pairs.

All written questions are graded for achievement by both the class instructor and the researcher. Interrater reliability is measured using Kendall’s W, which is a measure not only of the correlation of the two graders but the closeness of their grading, a value of 1.00 representing complete agreement (Huck, 2004). Interrater reliability of the free response achievement questions was determined by 100% parallel grading between the instructor and the researcher which resulted in a Kendall’s W of 0.910.

The scoring of the open-ended concept integration questions on the written tests was performed by the researcher using the flow chart in Figure 13 and the activity constructs. Interrater reliability of the concept integration questions was determined by parallel grading by the researcher and another organic instructor using the same grading rubric of 41 randomly selected tests from the entire semester. Kendall’s W was calculated at 0.977 for the grading reliability for the free response concept integration questions on these 41 tests.

Survey Instrument

Each student’s learning approach is measured using an online version of the Approaches and Study Skills Inventory for Students (ASSIST). The survey originated from a self report questionnaire, the Approaches to Study Inventory (ASI), developed by Noel Entwistle to measure the degree to which a student’s strategy is focused on developing deep meaning or acquiring superficial facts (Entwistle & Ramsden, 1983). Biggs (1987) developed a second inventory that was very similar to Entwistle’s. Since then these surveys have been adapted to specific research situations and used to measure the effect of or changes in student study
strategies (Biggs, 1987; Edmonson, 1989; Richardson, 2005; Speth et al., 2007). The most recent form, the Approaches and Study Skills Inventory for Students (ASSIST), was modified by Entwistle, et al. (2000) to include the strategic approach, a strategy used by the achievement driven student.

The choice to use this instrument is based on extensive, large studies of this survey with college students worldwide (Marsh, 2006). The construct validity testing by cluster and factor analysis, that has been performed by several researchers (Biggs, 1987; Speth et al., 2007); and a pilot study completed during spring semester 2008 by the author at the University of North Texas on students attending general chemistry and freshman biology classes.

This instrument, or a variation of it, has been used in 25 countries, mainly in Europe, Australia and Asia. Many different kinds of college students in a variety of disciplines have been included in the extensive reliability and validity testing. An international review article named the SAL survey (Student Approach to Learning survey and predecessor to ASSIST) one of “educational psychology’s most useful affective constructs” with “broad applicability and usefulness” due to its cross-cultural and cross-discipline validity (Marsh, 2006, p. 349). Marsh recommended the instrument, or a variation of it, as a measure of the intervening learning approach variables that affect long term educational goals and to determine the relationship of learning approach to other educational psychology constructs (Marsh, 2006).

In a pilot study at the University of North Texas by this author, 273 biology and chemistry students were surveyed using ASSIST. Students respond to 52 statements in an online survey using a five point Likert scale to indicate the degree to which the statement applies to them. Four to five statements were grouped into one subscale; and the total of thirteen sub-
scales were divided into three main learning approach scales: deep approach, strategic approach, and surface approach. The choice to use this instrument was based on the factor and cluster analyses detailed in the literature demonstrating that these sub-scales clustered consistently with specific approaches to learning (Entwistle, Nisbet, & Bromage, 2004; Entwistle, Tait et al., 2000; McCune & Entwistle, 2000). Cronbach alpha scores for the thirteen subscales in the pilot study ranged from .4 – .8, which are low, due to the low number of questions (four) in each subscale. However, these values are in line with Cronbach alphas of .4 – .8 for the subscales found in the literature (Edmonson, 1989; Taylor & Hyde, 2002). The reliability of the three main scales of Deep, Strategic and Surface learning was consistent in the pilot study as demonstrated by Cronbach alphas of .80 to .84. These compare favorably with literature values of .77 – .83 (Entwistle, Tait et al., 2000) and .65 – .75 (Speth et al., 2007) for the three main scales. Cronbach alpha scores of .8 demonstrate strong internal consistency for the major three categories.

In this study the same version of ASSIST was used to collect student online responses that were downloaded into a spreadsheet and analyzed in the statistical software program SPSS. The results were checked for reliability of internal consistency by calculating Cronbach’s alpha for the three scales: deep approach, strategic approach, and surface approach, and their thirteen sub-scales. For each question the Cronbach alpha coefficient, if the item were deleted, is close to the alpha coefficient if the item is included which demonstrates internal consistency for these questions as shown in Table 8. Exceptions to this are question numbers 23 and 52, highlighted in the table.
Question 52 is “I sometimes get ‘hooked’ on academic topics and feel I would like to keep on studying them.” It is grouped in the “Interest in Ideas” subscale, which is included in the Deep Approach scale. With question 52 included, the Cronbach alpha coefficient for the subscale for the pre-course survey is .161, but increases to .700 when the question is excluded. In the post survey the alpha was only slightly different, .557 on the pre-survey and .600 on the post-survey. In investigating the reason for the inconsistent answer, it was found that the Likert scale on the survey form was reversed for this question and this question only. Therefore, it was impossible to determine if the students’ responses to this question were what they had intended. For this reason the question was excluded from both the pre- and post-survey data.

Question 23 is “Often I find myself questioning things I hear in lecture or read in books.” It is grouped in the “Use of Evidence” subscale, which is included in the Deep Approach scale. With question 23 included, the Cronbach alpha coefficient for Use of Evidence subscale for the pre-course survey is .392, but increases to an acceptable .513 when excluded. On the post survey, Cronbach alpha coefficient is .557 with the question and .600 without the question. The pre- and post-survey means for the question were very close, indicating little change in response to the question. It was decided to exclude question 23 data for both surveys, due to the low item correlation and Cronbach alpha coefficient.

The alpha coefficients’ range for the thirteen subscales is from .38-.80. A few are low, due the small number of questions (four) in each sub-scale. However, these values are directly in line with those found in the literature (Edmonson, 1989; Taylor & Hyde, 2002). Because of the small number of questions, inter-item correlations were calculated for each subscale. All the correlations were .3 or greater, which is considered moderately related (Pallant, 2001).
Table 8

**ASSIST survey question consistency (pre-course N = 101, post-course N = 205)**

<table>
<thead>
<tr>
<th>Question / Subscale</th>
<th>Mean</th>
<th>Cronbach Alpha Coefficient</th>
<th>Inter-Item Correlation</th>
<th>Alpha Scale if Item Deleted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Deep Approach Scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.84</td>
<td>.88</td>
<td>.530</td>
<td>.596</td>
</tr>
<tr>
<td>Seeking Meaning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.67</td>
<td>.74</td>
<td>.346</td>
<td>.421</td>
</tr>
<tr>
<td>4</td>
<td>4.03</td>
<td>3.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>3.79</td>
<td>3.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>3.48</td>
<td>3.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>3.22</td>
<td>3.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relating Ideas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.61</td>
<td>.65</td>
<td>.284</td>
<td>.314</td>
</tr>
<tr>
<td>11</td>
<td>3.87</td>
<td>3.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>3.88</td>
<td>3.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>3.09</td>
<td>2.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>3.07</td>
<td>3.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use of Evidence</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.51*</td>
<td>.60*</td>
<td>.259*</td>
<td>.335*</td>
</tr>
<tr>
<td>9</td>
<td>3.60</td>
<td>3.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>3.27</td>
<td>3.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>3.67</td>
<td>3.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>4.19</td>
<td>3.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interest in Ideas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.70*</td>
<td>.74*</td>
<td>.436*</td>
<td>.491*</td>
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<tr>
<td>13</td>
<td>3.12</td>
<td>3.09</td>
<td></td>
<td></td>
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<tr>
<td>26</td>
<td>3.46</td>
<td>3.42</td>
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<td>39</td>
<td>3.51</td>
<td>3.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>2.77</td>
<td>3.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metacognition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.67</td>
<td>.73</td>
<td>.338</td>
<td>.410</td>
</tr>
<tr>
<td>7</td>
<td>3.65</td>
<td>3.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>3.70</td>
<td>3.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>3.59</td>
<td>3.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>3.82</td>
<td>3.81</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Calculation excludes highlighted question – either question number 23 or 52
The exception was the Achieving subscale which had a correlation of .139 for the pre-survey which increased to .309 on the post survey indicating that students responded more consistently to the achievement motivation questions at the end of the semester.

Table 9 shows Cronbach alpha coefficients for each of the three major learning approach scales: deep approach, strategic approach, and surface approach. These are the three dependent measures of the study.

Table 9

<table>
<thead>
<tr>
<th>Approach Scale</th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep</td>
<td>.84</td>
<td>.87</td>
</tr>
<tr>
<td>Strategic</td>
<td>.74</td>
<td>.85</td>
</tr>
<tr>
<td>Surface</td>
<td>.82</td>
<td>.78</td>
</tr>
</tbody>
</table>

The reliability of the three scales is consistent from Cronbach alpha coefficients of .74 - .88. This compares favorably with literature values of .77 - .83 (Entwistle, Tait et al., 2000) and .65 - .75 (Speth et al., 2007). Cronbach alpha coefficients of .80 or more demonstrate strong internal consistency for the major three categories.

**Dependent variables**

**Research question 1**

The two dependent variables for the first research question are achievement and concept integration. Student learning developmental stages are evaluated by measuring achievement and concept integration through a topic and across topics. The achievement
measure is used to determine development stages I and II, while concept integration is used for developmental stages III and IV.

The two dependent variables, concept integration and achievement, are measured using the two-tiered clicker questions and the free response hourly and final examination questions. Two scores are obtained for each measurement point – one for achievement and one for concept integration.

*Research question 2*

The dependent variable for the second research question is student learning approach. Learning approach is measured using the ASSIST survey both at the beginning and end of the semester. Three scores are used to determine learning approach: deep, strategic score, and surface approach.

*Research question 3*

The dependent variables for the third research question are achievement and concept integration as measured by the questions on the hourly and final examinations. Achievement data from the hourly and final exams is used to measure developmental stages I and II. Concept integration is measured by evidence of concept linkage in student free response answers on those exams as measurement of developmental levels III and IV.

*Independent variables*

The independent variables for all the research questions are the time on a topic and across related topics using guided inquiry activity worksheets. The instructor uses guided inquiry worksheets for nearly all classes; however, only six activities on three topics are examined in this study. Quantitative measurements of the dependent variables, achievement
Table 10

Summary of Dependent Variable Measures for Research Questions 1 and 3

<table>
<thead>
<tr>
<th>Topic</th>
<th>Occasion</th>
<th>Assessment</th>
<th>Instructor’s Activity</th>
<th>Type</th>
<th>Variables Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid / Base</td>
<td>1st Activity</td>
<td>3A</td>
<td>Clicker</td>
<td></td>
<td>AB1a</td>
</tr>
<tr>
<td></td>
<td>2nd Activity</td>
<td>3B</td>
<td>Clicker</td>
<td></td>
<td>AB2a</td>
</tr>
<tr>
<td></td>
<td>Post 2nd Activity</td>
<td></td>
<td>Clicker</td>
<td></td>
<td>AB3a</td>
</tr>
<tr>
<td></td>
<td>End of Topic</td>
<td></td>
<td>Hourly Exam</td>
<td></td>
<td>AB4a</td>
</tr>
<tr>
<td>Nucleophilic Substitution</td>
<td>1st Activity</td>
<td>9A</td>
<td>Clicker</td>
<td></td>
<td>NS1a</td>
</tr>
<tr>
<td></td>
<td>2nd Activity</td>
<td>9B</td>
<td>Clicker</td>
<td></td>
<td>NS2a</td>
</tr>
<tr>
<td></td>
<td>Post 2nd Activity</td>
<td></td>
<td>Clicker</td>
<td></td>
<td>NS3a</td>
</tr>
<tr>
<td></td>
<td>End of Topic</td>
<td></td>
<td>Hourly Exam</td>
<td></td>
<td>NS4a</td>
</tr>
<tr>
<td>Electrophilic Addition</td>
<td>1st Activity</td>
<td>12B</td>
<td>Clicker</td>
<td></td>
<td>EA1a</td>
</tr>
<tr>
<td></td>
<td>2nd Activity</td>
<td>12C</td>
<td>Clicker</td>
<td></td>
<td>EA2a</td>
</tr>
<tr>
<td></td>
<td>Post 2nd Activity</td>
<td></td>
<td>Clicker</td>
<td></td>
<td>EA3a</td>
</tr>
<tr>
<td></td>
<td>End of Topic</td>
<td></td>
<td>Hourly Exam</td>
<td></td>
<td>EA4a</td>
</tr>
<tr>
<td>Across Topics</td>
<td>End of Semester</td>
<td></td>
<td>Final Exam</td>
<td>Fa</td>
<td>Fc</td>
</tr>
</tbody>
</table>

*not collected due to end of semester
and concept integration, are made during class for all six activities, for two delay points, three hourly exams, and the final examination. The variables are shown in Table 10 and correspond to the assessment questions in Appendix D.

Study Design

A mixed quantitative qualitative approach is used in this study. The primary focus of the study is student achievement and concept integration during and after instruction in first semester organic chemistry topics. The course under study uses a unique pedagogy – active group learning with guided inquiry activities. There is not a comparable course for a control. When no suitable control group is possible the study design is pre-experimental using a single group interrupted time investigation (Creswell, 2003). Assessment of students’ achievement and concept integration are made at strategic intervals. Achievement and concept integration are measured quantitatively over three organic chemistry topics (acid-base, nucleophilic substitution, and electrophilic addition), and over three time frames (immediate, intermediate, and at the end of the semester). Immediate integration is measured quantitatively within each topic using clickers, intermediate integration is measured with the hourly exam over each topic, and overall concept integration is measured across the three chemistry topics with the final examination.

Each of the three topics is taught using two prepared in-class activity sheets scheduled for two periods for a total of six class periods. Occasionally the topic’s second activity extends to a third class period. As detailed in Table 10, immediate achievement and concept integration are measured using clickers during each of the six activities and approximately one week after the completion of the second worksheet within a topic. All other achievement and concept integration...
development measurements are made on the three topic hourly examinations, and the final examination. Learning approach is measured at the beginning and end of the semester.

Methodology

Data Analysis

Descriptive statistics for all dependent and intervening variables evaluated include normality, histograms, mean, median, skewness and kurtosis. Since all of the data in the study are interval data, inferential statistics are used to evaluate each research question.

The choice for statistical analysis is based on the data and model assumptions. The first research question calls for comparisons of means for achievement and concept integration on multiple occasions. There are three kinds of repeated measures studies: repeated tests under different conditions, comparison of different tests, and a longitudinal study. This research question falls into all three categories. For achievement and concept integration, comparisons were made across time within a topic, and across related topics. A determination was made to test for an interaction effect between these two. For that reason a higher-order design with within-subjects factors is performed.

The traditional method in the literature for this type of analysis is multiple ANOVAs with a Bonferri adjustment to decrease the likelihood of Type II error. ANOVA assumes homogeneity of treatment variance and sphericity, but several adjustments are available to compensate for violation of this assumption, most commonly used is the Greenhouse–Geisser epsilon hat. This adjustment is considered overly conservative. The univariate ANOVA is also sensitive to correlations between data and assumes the measures are independent of one another. Since all
within-subjects studies violate these last two criteria, a better data analysis procedure is required (Maxwell & Delaney, 2004).

A second choice is the MANOVA, which does not have the severe restrictions that the univariate approach has. Unlike ANOVA, MANOVA is robust to non-sphericity and has the added advantage that no contrast can be significant unless the overall omnibus test is significant (Maxwell & Delaney, 2004). Both ANOVA and MANOVA assume balanced data, that each occasion has approximately the same number of data points. If there is unbalanced data, such as in this study, missing data needs to be treated listwise rather than pairwise. This can cause a significant loss of data and thus statistical power.

A third choice, a mixed model such as the maximum likelihood approach can compensate for missing data, such as in this study. This approach yields correct results with correlated data found in within-subjects designs while effectively dealing with missing data or missing cells, something the MANOVA and ANOVA cannot do (Maxwell & Delaney, 2004). The maximum likelihood approach was not used because by treating missing data pairwise the same individual student’s performance is not considered and reduces the validity of the study. Missing data may be skewed to stronger students or weaker students or in some other fashion that could affect the outcome. For those reasons the MANOVA with a Greenhouse-Geisser correction and the more stringent listwise treatment of missing data are used for this study. This is a very conservative approach.

The second research question examines changes in the students’ learning approaches from the beginning to the end of the semester. For this analysis a simple paired (dependent) t-
test is used. Again, the missing data are treated listwise so that the same students are compared.

The third research question studies the relationship of student learning approach and deeper understanding (concept integration) and algorithmic learning (achievement). There are two reasonable choices for this analysis – more than one multiple regression or one canonical correlation analysis (CCA). The CCA is chosen because more than one multiple regression would be needed to examine the correlation of these variables, and, like multiple univariate ANOVAs, the risk for a type II error increases with each additional test.

Canonical correlation analysis evaluates two sets of correlated variables. Each student has three correlated learning approach scores –deep approach, surface and strategic. The scores are converted to standard z-scores so can be compared. Using CCA, a synthetic variable composed of a set of predicator variables (in this case the three learning approaches) is compared to a second synthetic variable comprised of criterion variables such as achievement and concept integration. The multivariate-shared relationship of the two synthetic variables is then evaluated. It is argued that CCA is a more valid and realistic approach for behavior variables that are often correlated to each other than other methods (Sherry & Henson, 2005). Some references believe that CCA gives as much information on effect size as the simpler multiple regression analyses (Isaac & Michael, 1995). For this study CCA was chosen because it more accurately resembles the complex interaction of the multiple related variables measured.

Study Limitations

This study’s greatest weakness is its external validity. High external validity means that the study findings can be applied to other populations. The differences between the way this
class is taught and the traditional lecture include use of scaffolded guided inquiry worksheets, use of “clickers” for two way feedback, electronic homework that permits structure drawing, student engagement, and the potential for social learning through the in-class groups. Because of this multiple treatment interference, it is not possible to have a comparable control group. However, future studies based on the results of this study may be able to use a quasi-experimental design.

There are three threats to internal validity that need to be addressed – threats to construct validity, validity of testing instruments, and statistical conclusion validity. Is the important variable actually measured? Threats to construct validity may be caused by fuzzy definitions of the measurement variable. This study addresses the issue through the construction of knowledge constructs and test questions for each activity. The activities, their intended knowledge constructs, and the questions that measure the constructs were reviewed for content and testing instrument validity by three organic professors with long careers in other institutions. Their suggestions were implemented whenever feasible (Isaac & Michael, 1995).

Statistical validity is addressed through the selection of conservative statistical analyses and assurances that assumptions for that test are met. As discussed in the last section much data are not used in order to preserve the highest possible accuracy through listwise treatment of missing data. However, there is a tradeoff in that the reduced number in the sample reduces the statistical power of the test (Isaac & Michael, 1995).

The validity of clicker measures is addressed by not showing the class student responses to the study questions. This helped avoid a diffusion effect from the student seeing
the overall class response and thus enabled use of the same question for a time delay testing point.

Summary

The topic of this study is the interrelationship of learning approach (deep, strategic, and surface) with learning outcomes (achievement and concept integration). Before investigating this relationship, learning approach and the learning outcomes of achievement and concept integration are measured separately.

The two dependent variables, achievement and concept integration, are investigated over time both within a topic and time across related topics. Achievement measures student learning at developmental stages I and II. Concept integration measures developmental stages III and IV. Thirteen assessments are used for measurement and a Repeated Measures MANOVA with pairwise comparisons is used to investigate differences, if any.

Students' learning approaches are measured to determine what changes, if any, occur over the semester in a large organic class using guided inquiry. Learning approaches are measured at the beginning and end of the course using the ASSIST survey, and scores are calculated for deep, strategic, and surface learning approaches. A paired t-test is used to determine if significant changes occur over the semester.

The relationship between learning approach and learning outcomes is investigated using data from the first two analyses. To be statistically conservative, the students’ beginning learning approach scores for deep, strategic, and surface learning are compared to the achievement and concept integration scores from the written examinations only. Given the multiple variables, canonical correlation analysis is used to create a single criterion variable for
achievement and concept integration, and a single predictor variable for the three student learning approaches – deep, strategic, and surface. The relationship between criterion variable and predictor variable is then determined.
CHAPTER IV

RESULTS

First Research Question – Effect of Time on Achievement and Concept Integration

*Data Analysis*

The investigation’s purpose was to determine the effect (if any) of time using in-class guided inquiry activities both *within* a topic and *across* related topics on a student’s achievement and concept integration. The three topics were acid-base, nucleophilic substitution, and electrophilic addition reactions. *Within* each topic the dependent variables, achievement and concept integration, were measured on four occasions representing two concurrent measures (at the time of two sequential in-class activities), a delayed measure (one week after the second activity class), and an intermediate measure (hourly exam). The end of the semester prevented the one week delayed measure after the second activity in the third topic. The final exam was included as a cumulative measure and the delayed measure for the third topic was not collected so there were a total of twelve measurement occasions. On all these occasions two variables were measured on linked questions – achievement and concept integration. All the in-class data were collected through the student response system (clickers) and the hourly and final written, multipart free-response questions.

The means for each of these measures are given in Table 11. Recall that the scale of 0 – 4 represents the students’ achievement or concept integration as discussed in the previous chapter. The range of the achievement means for all occasion was 1.7 - 3.5 and the concept integration mean was 0.8 - 3.4.
Table 11

Means of the Achievement and Concept Integration Measures

<table>
<thead>
<tr>
<th>Topic</th>
<th>Occasion</th>
<th>Type</th>
<th>N</th>
<th>Variable Means*</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Concept</td>
<td>Achieve</td>
</tr>
<tr>
<td>1: Acid / Base</td>
<td></td>
<td>Concurrent Clicker (1st Activity)</td>
<td>104</td>
<td>3.4</td>
<td>3.8</td>
</tr>
<tr>
<td>1</td>
<td>Concurrent Clicker (2nd Activity)</td>
<td>104</td>
<td>2.7</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Delayed Clicker</td>
<td>96</td>
<td>3.3</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Exam Question</td>
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<td>1.7</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2: Nucleophilic Substitution</td>
<td></td>
<td>Concurrent Clicker (1st Activity)</td>
<td>105</td>
<td>1.5</td>
<td>3.3</td>
</tr>
<tr>
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<td>Concurrent Clicker (2nd Activity)</td>
<td>99</td>
<td>1.9</td>
<td>1.9</td>
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</tr>
<tr>
<td>2</td>
<td>Delayed Clicker</td>
<td>102</td>
<td>1.7</td>
<td>3.2</td>
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</tr>
<tr>
<td>3</td>
<td>Exam Question</td>
<td>109</td>
<td>0.8</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3: Electrophilic Addition</td>
<td></td>
<td>Concurrent Clicker (1st Activity)</td>
<td>103</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>1</td>
<td>Concurrent Clicker (2nd Activity)</td>
<td>93</td>
<td>3.4</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Delayed Clicker</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Exam Question</td>
<td>103</td>
<td>1.7</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4: Final Exam</td>
<td></td>
<td>Exam Question</td>
<td>104</td>
<td>1.6</td>
<td>1.7</td>
</tr>
</tbody>
</table>

*Max = 4.0

A two-way within-subjects multivariate analysis of variance was performed on the achievement and concept integration dependent variables, with two independent variables,
time within topic and across topics. The delayed measures clicker assessment taken one week after the first two topics was not included in the analysis due to a missing cell. This cell included the delayed measure for the third topic, electrophilic addition, which was not conducted due to the end of the semester.

The data were analyzed using SPSS Multivariate Repeated Measures. The Repeated Measures analysis was justified because each question measured the same variable attribute for that topic, although the identical question was not used for each measurement (Maxwell & Delaney, 2004). Statistical assumptions for MANOVA were tested by checking for normality, linearity, univariate and multivariate outliers, sphericity, and multicollinearity. All Mahalanobis distances were much less that the chi squared critical value. Normality was not always observed with each variable, but MANOVA is considered robust against this violation with sample sizes greater than thirty (Maxwell & Delaney, 2004). However, MANOVA is sensitive to outliers (Maxwell & Delaney, 2004) so outliers were evaluated for their potential effect on the statistical analysis by comparing the 5% trimmed mean with the actual mean for each variable. In all cases the 5% trimmed mean was close enough to the overall mean to allow the test to be used. Using both Bartlett’s and Mauchly’s tests for sphericity, the sphericity assumption was violated, so the Greenhouse-Geisser correction was used to adjust the degrees of freedom for a more rigorous test of statistical significance. There were no other violations of assumptions. All computations were analyzed using a probability level of .05. All missing data was treated listwise for the nine dependent variables, therefore the number of students was reduced to only those who participated in all of the measures made during the semester \((N = 59)\).
The null hypothesis being tested for the first part of the first research question is: A student who completes one semester of guided inquiry organic chemistry in a large class will show no significant differences in achievement with time, either within a topic or between related topics. Table 12 gives the test results for this hypothesis. All test results were statistically significant at a probability level of .05 or less using the Greenhouse-Geisser correction for non-sphericity. The achievement scores were significantly different across topics, $F = 53.40 \ (2.0, 111.0), \ p < .001$. The within topic omnibus test result was significant, $F = 16.42 \ (1.5, 83.1), \ p < .001$ and the interaction of across topics and within topics were $F \ (3.5, 194.3) = 40.75, \ p < .001$. Therefore the null hypothesis is rejected and there is a statistical difference in achievement for both within and across topics.

Table 13 shows the MANOVA results for achievement using the entire model and hypothetical degrees of freedom. The Wilks’ $\Lambda$ for across topics was .327. Since 1 - Wilks’ $\Lambda$ provides an $r^2$ type measure; the effect size for across topics is calculated to be .673. This means that 67% of the variance in achievement scores is associated depending on the topic studied. The Wilks’ $\Lambda$ for within topics was .660, resulting in an effect size of .340 that explains 34% of the variance in achievement scores while studying a particular topic. The Wilks’ $\Lambda$ for the interaction of across and within topics was 0.233, with an effect size of 0.767, demonstrating the large interaction of the two independent variables (progression through a topic and between topics).
### Table 12

**MANOVA Tests of Within-Subjects Effects on Achievement (N=59)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Correction</th>
<th>Type III SOS</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across Topics</td>
<td>Sphericity Assumed</td>
<td>65.63</td>
<td>2.0</td>
<td>32.81</td>
<td>53.40</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>65.63</td>
<td>2.0</td>
<td>33.10</td>
<td>53.40</td>
<td>.000</td>
</tr>
<tr>
<td>Error(Across)</td>
<td>Sphericity Assumed</td>
<td>68.82</td>
<td>112.0</td>
<td>0.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>714.08</td>
<td>111.0</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within Topic</td>
<td>Sphericity Assumed</td>
<td>45.30</td>
<td>2.0</td>
<td>22.65</td>
<td>16.42</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>45.30</td>
<td>1.5</td>
<td>30.53</td>
<td>16.42</td>
<td>.000</td>
</tr>
<tr>
<td>Error(Within)</td>
<td>Sphericity Assumed</td>
<td>154.48</td>
<td>112.0</td>
<td>1.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>154.48</td>
<td>83.1</td>
<td>1.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Across Topic *</td>
<td>Sphericity Assumed</td>
<td>114.66</td>
<td>4.0</td>
<td>40.75</td>
<td>40.75</td>
<td>.000</td>
</tr>
<tr>
<td>Within Topic</td>
<td>Greenhouse-Geisser</td>
<td>114.66</td>
<td>3.5</td>
<td>40.75</td>
<td>40.75</td>
<td>.000</td>
</tr>
<tr>
<td>Error (Across *</td>
<td>Sphericity Assumed</td>
<td>157.57</td>
<td>224.0</td>
<td>0.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within)</td>
<td>Greenhouse-Geisser</td>
<td>157.57</td>
<td>194.3</td>
<td>0.81</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(α = .05)

### Table 13

**Wilks’ Lambda for Achievement (N=59)**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Wilks’ Λ</th>
<th>F</th>
<th>Hypothesis df</th>
<th>Error df</th>
<th>p</th>
<th>Partial η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across Topics</td>
<td>.327</td>
<td>56.70</td>
<td>2.0</td>
<td>55.0</td>
<td>.000</td>
<td>.673</td>
</tr>
<tr>
<td>Within Topics</td>
<td>.660</td>
<td>14.14</td>
<td>2.0</td>
<td>55.0</td>
<td>.000</td>
<td>.340</td>
</tr>
<tr>
<td>Across Topic * Within Topic</td>
<td>.233</td>
<td>43.53</td>
<td>4.0</td>
<td>53.0</td>
<td>.000</td>
<td>.767</td>
</tr>
</tbody>
</table>
Table 14 shows the pairwise comparison for the across topics effect. Achievement in the middle topic, nucleophilic substitution, was significantly different from that in either the first topic, acid-base chemistry, or the third topic, electrophilic addition. The achievement measures for the first and third topic are not significantly different from each other. A bar graph of these data is provided in Figure 14.

Table 14

Pairwise Comparisons for Across Topic Effects on Achievement (N=59)

<table>
<thead>
<tr>
<th>Topic</th>
<th>Topic</th>
<th>Mean difference</th>
<th>Std. error</th>
<th>p</th>
<th>95% Confidence Interval for difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid / Base</td>
<td>A/B NS</td>
<td>0.708*</td>
<td>0.081</td>
<td>.000</td>
<td>0.545 - 0.871</td>
</tr>
<tr>
<td></td>
<td>A/B EA</td>
<td>-0.094</td>
<td>0.088</td>
<td>.293</td>
<td>-0.279 - 0.083</td>
</tr>
<tr>
<td>Nucleophilic substitution</td>
<td>A/B NS</td>
<td>-0.708*</td>
<td>0.081</td>
<td>.000</td>
<td>-0.871 - -0.545</td>
</tr>
<tr>
<td></td>
<td>A/B EA</td>
<td>-0.801*</td>
<td>0.085</td>
<td>.000</td>
<td>-0.971 - -0.632</td>
</tr>
<tr>
<td>Electrophilic addition</td>
<td>A/B NS</td>
<td>0.094</td>
<td>0.088</td>
<td>.293</td>
<td>-0.083 - 0.270</td>
</tr>
<tr>
<td></td>
<td>A/B EA</td>
<td>0.801*</td>
<td>0.085</td>
<td>.000</td>
<td>0.632 - 0.971</td>
</tr>
</tbody>
</table>

* The mean difference is significant at \( \alpha = .05 \)

A/B = Acid base   NS = Nucleophilic substitution   EA = Electrophilic addition
Figure 14. Comparison of achievement across topics.

Missing from the bar graph is the mean score for the delayed clicker question from electrophilic addition, which was not collected due to the end of the semester. The achievement scores for the nucleophilic substitution topic were lower overall than those of the acid/base and electrophilic addition topics. Note that the hourly examination achievement scores were overall lower than the in-class clicker achievement scores.

The pairwise comparison for the within topic effect is shown in Table 15. Achievement scores for all three topic measures were significantly different from each other. Figure 15 visually compares the achievement means for each measurement within each topic. Although not obvious from the bar chart, the statistical analysis shows that there is a significant difference among the three measurement occasions – the first and second clicker questions and the hourly exams. Note the mean difference from the clicker question for the first activity in the three topics. The second clicker question mean was 0.456 higher and the exam question
mean was 0.719 higher. Therefore the average achievement score increased from one measurement to the next within a topic.

Table 15

**Pairwise Comparisons for Within Topic Effects on Achievement (N=59)**

<table>
<thead>
<tr>
<th>Occasion</th>
<th>Question</th>
<th>Mean difference</th>
<th>Std. error</th>
<th>p</th>
<th>95% Confidence interval for difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>Click1</td>
<td>Click1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Click2</td>
<td></td>
<td>0.456*</td>
<td>0.091</td>
<td>.000</td>
<td>0.274</td>
</tr>
<tr>
<td>Exam</td>
<td></td>
<td>0.719*</td>
<td>0.157</td>
<td>.000</td>
<td>0.404</td>
</tr>
<tr>
<td>Click2</td>
<td>Click1</td>
<td>-0.456*</td>
<td>0.091</td>
<td>.000</td>
<td>-0.638</td>
</tr>
<tr>
<td>Act 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exam</td>
<td></td>
<td>0.263*</td>
<td>0.124</td>
<td>.039</td>
<td>0.014</td>
</tr>
<tr>
<td>Exam</td>
<td>Click1</td>
<td>-0.719*</td>
<td>0.157</td>
<td>.000</td>
<td>-1.034</td>
</tr>
<tr>
<td>Exam</td>
<td>Click2</td>
<td>-0.263*</td>
<td>0.124</td>
<td>.039</td>
<td>-0.512</td>
</tr>
</tbody>
</table>

* The mean difference is significant at the .05 level.

Click1 = 1st activity clicker question  
Click2 = 1st activity clicker question  
Exam = Hourly exam

*Figure 15. Comparison of student achievement within each topic.*
Figure 15 demonstrates that in general the achievement scores that the first clicker question for the average topic produced the highest achievement score. Interestingly, there was no learning extinction evident between the clicker question given after the second activity and the same question given a week later.

The null hypothesis being tested for the second part of the first research question is: Students who complete one semester of guided inquiry organic in a large class will show no significant differences in concept integration with time within or between related topics. Table 16 gives MANOVA results for this hypothesis. The Greenhouse-Geisser correction for the degrees of freedom for each aspect of the model is listed in the table. Even with the reduced degrees of freedom, all tests results were statistically significant at a probability of .05 or less. The concept integration scores were significantly different across topics, $F (1.1, 65.5) = 13.60$, $p < .001$. The within topic omnibus test result was significant, $F (1.4, 83.1) = 10.90$, $p < .001$ and the interaction of across topics and within topics results were $F (1.3, 74.9) = 4.36$, $p = .031$. Therefore the null hypothesis is rejected and there is a statistical difference in concept integration both within topics and across topics.

Table 17 shows the MANOVA results for concept integration using the hypothetical degrees of freedom. The Wilks’ $\Lambda$ for topic was .228. Since 1 - Wilks’ $\Lambda$ provides an $r^2$ type measure; the effect size for across topics is .77. This means that 77% of the variance in concept integration scores is due to the topic. The Wilks’ $\Lambda$ for within topic was .660, resulting in an effect size of .34 that explains 34% of the variance in concept integration scores with progression through an individual topic. The Wilks’ $\Lambda$ for the interaction of across and within
topics was .542, with an effect size of .46, demonstrating an interaction of 46% between the

two independent variables (progression through a topic and between topics).

Table 16
**MANOVA Tests of Within-Subjects Effects on Concept Integration (N=59)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Adjustment</th>
<th>Type III SOS</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across Topics</td>
<td>Sphericity Assumed</td>
<td>167.47</td>
<td>2.0</td>
<td>83.74</td>
<td>13.60</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>167.47</td>
<td>1.1</td>
<td>148.23</td>
<td>13.60</td>
<td>.000</td>
</tr>
<tr>
<td>Error(Across)</td>
<td>Sphericity Assumed</td>
<td>714.08</td>
<td>116.0</td>
<td>6.16</td>
<td>10.91</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>714.08</td>
<td>65.5</td>
<td>148.23</td>
<td>10.91</td>
<td>.000</td>
</tr>
<tr>
<td>Within Topic</td>
<td>Sphericity Assumed</td>
<td>159.28</td>
<td>2.0</td>
<td>79.64</td>
<td>10.90</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>159.28</td>
<td>1.4</td>
<td>111.23</td>
<td>10.90</td>
<td>.000</td>
</tr>
<tr>
<td>Error(Within)</td>
<td>Sphericity Assumed</td>
<td>847.61</td>
<td>116.0</td>
<td>7.31</td>
<td>10.21</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>847.61</td>
<td>83.1</td>
<td>7.31</td>
<td>10.21</td>
<td>.000</td>
</tr>
<tr>
<td>Across Topic *</td>
<td>Sphericity Assumed</td>
<td>108.38</td>
<td>4.0</td>
<td>27.10</td>
<td>4.36</td>
<td>.002</td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>108.38</td>
<td>1.3</td>
<td>83.90</td>
<td>4.36</td>
<td>.031</td>
</tr>
<tr>
<td>Error (Across *</td>
<td>Sphericity Assumed</td>
<td>1442.73</td>
<td>232.0</td>
<td>6.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Greenhouse-Geisser</td>
<td>1442.73</td>
<td>74.9</td>
<td>6.22</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(α = .05)

Table 17
**Wilks’ Lambda for Concept Integration (N=59)**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Wilks' Λ</th>
<th>F</th>
<th>Hypothesis df</th>
<th>Error df</th>
<th>p</th>
<th>Partial η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across Topics</td>
<td>.228</td>
<td>96.46</td>
<td>2.0</td>
<td>57.0</td>
<td>.000</td>
<td>.772</td>
</tr>
<tr>
<td>Within Topics</td>
<td>.660</td>
<td>14.69</td>
<td>2.0</td>
<td>57.0</td>
<td>.000</td>
<td>.340</td>
</tr>
<tr>
<td>Across Topic * Within Topic</td>
<td>.542</td>
<td>11.60</td>
<td>4.0</td>
<td>55.0</td>
<td>.000</td>
<td>.458</td>
</tr>
</tbody>
</table>
Table 18 shows the pairwise comparison for the across topics effect. Concept integration in the middle topic, nucleophilic substitution, was significantly different from that in either the first topic, acid-base chemistry, or the third topic, electrophilic addition. The concept integration measures for the first and third topic are not significantly different from each other. This is identical to the achievement finding.

Table 18

*Pairwise Comparisons for Across Topic Effects on Concept Integration (N=59)*

<table>
<thead>
<tr>
<th>Topic</th>
<th>Topic</th>
<th>Mean difference</th>
<th>Std. error</th>
<th>p</th>
<th>95% Confidence interval for difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>Acid / Base</td>
<td>A/B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NS</td>
<td></td>
<td>1.31*</td>
<td>0.094</td>
<td>.000</td>
<td>1.12</td>
</tr>
<tr>
<td>EA</td>
<td></td>
<td>0.29</td>
<td>0.306</td>
<td>.342</td>
<td>-0.32</td>
</tr>
<tr>
<td>Nucleophilic substitution</td>
<td>A/B</td>
<td>-1.31*</td>
<td>0.094</td>
<td>.000</td>
<td>-1.50</td>
</tr>
<tr>
<td>NS</td>
<td></td>
<td>-1.02*</td>
<td>0.325</td>
<td>.003</td>
<td>-1.67</td>
</tr>
<tr>
<td>EA</td>
<td></td>
<td>-1.02*</td>
<td>0.325</td>
<td>.003</td>
<td>-1.67</td>
</tr>
<tr>
<td>Electrophilic addition</td>
<td>A/B</td>
<td>-0.29</td>
<td>0.306</td>
<td>.342</td>
<td>-0.91</td>
</tr>
<tr>
<td>NS</td>
<td></td>
<td>1.02*</td>
<td>0.325</td>
<td>.003</td>
<td>0.37</td>
</tr>
<tr>
<td>EA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The mean difference is significant at $\alpha = .05$ level.

A/B = Acid base  NS = Nucleophilic substitution  EA = Electrophilic addition
Figure 16. Comparison of concept integration across topics.

Figure 17 is a bar graph of the results. Missing from the bar graph is the mean score for the delayed clicker question from electrophilic addition, which was not collected due to the end of the semester. The concept integration scores for the nucleophilic substitution topic were lower overall than those of the acid/base and electrophilic addition topics. This finding is similar to the achievement finding, but the decrease was greater for concept integration and therefore more readily detected visually in the bar graph. Note that the hourly examination concept integration scores were overall lower than the in-class clicker concept integration scores. This finding is also similar to that of achievement but the decrease is much larger. The lowest concept integration score for the semester was for the written hourly examination question for the second topic, nucleophilic substitution.

The pairwise comparison for the within topic effect is shown in Table 19. Concept integration for the fourth measures (hourly exam questions) is significantly different from either the other measurements on each topic (in-class clicker questions). Figure 17 visually compares the means for concept integration of both measurements within each topic. The concept integration findings are similar to the achievement findings but more dramatic.
Table 19

Pairwise Comparisons for Within Topic Effects on Concept Integration (N=59)

<table>
<thead>
<tr>
<th>Occasion</th>
<th>Question</th>
<th>Mean difference</th>
<th>Std. error</th>
<th>p</th>
<th>95% Confidence interval for difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>Click1</td>
<td>Click1</td>
<td>-0.497</td>
<td>0.327</td>
<td>.133</td>
<td>-1.151</td>
</tr>
<tr>
<td></td>
<td>Click2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exam</td>
<td>0.831*</td>
<td>0.175</td>
<td>.000</td>
<td>0.480</td>
</tr>
<tr>
<td>Click2</td>
<td>Click1</td>
<td>0.497</td>
<td>0.327</td>
<td>.133</td>
<td>-0.157</td>
</tr>
<tr>
<td></td>
<td>Act 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exam</td>
<td>1.328*</td>
<td>0.332</td>
<td>.000</td>
<td>0.662</td>
</tr>
<tr>
<td>Exam</td>
<td>Click1</td>
<td>-0.831*</td>
<td>0.175</td>
<td>.000</td>
<td>-1.181</td>
</tr>
<tr>
<td></td>
<td>Click2</td>
<td>-1.328*</td>
<td>0.332</td>
<td>.000</td>
<td>-1.993</td>
</tr>
</tbody>
</table>

* The mean difference is significant at the .05 level.

Click1 = 1\(^{st}\) activity clicker question  
Click2 = 2\(^{nd}\) activity clicker question  
Exam = Hourly exam

![Concept Integration Score](image)

**Figure 17.** Comparison of student concept integration within each topic.

**Discussion**

The fact that the concept integration scores for each occasion were generally equal to or significantly lower than the achievement scores suggests that students can perform on
achievement questions without complete understanding. The achievement questions are not an accurate measure of conceptual understanding (D. M. Bunce et al., 1991; Gabel et al., 1984; Nakhleh & Mitchell, 1993; Nurrenbern & Pickering, 1987).

Interestingly, it seems that the students’ concept integration was more closely associated with the topic than with the amount of time spent within a particular topic. The results from the first and the third topic were not significantly different from each other but the second topic was. The students ended the semester with the same integration of a first semester organic topic, electrophilic addition, as they began the semester with second semester general chemistry topic. The lowest concept integration means in the semester were for the middle topic, nucleophilic substitution.

The first topic was acid-base chemistry that is taught in depth in second semester general chemistry, the prerequisite to this course (where students must receive a C or better to continue in organic chemistry). The first clicker question covered concepts taught in the previous semester so we would expect that students had some integration of these concepts in an inorganic framework, and we can use this question as a marker of where students were at the end of general chemistry. The second clicker question in the acid-base topic applied the concepts to carbon chemistry, a new situation for these students. Not surprisingly given the new application the integration measure decreased with the second question, but was not zero since the students had some prior framework on which to build.

The second topic, nucleophilic substitution, is the first time during the semester that students encounter the concepts of nucleophiles and electrophiles. These concepts are very closely related to acids and bases except that the bond is to carbon, not hydrogen. There are
other differences, but in this situation the conceptual similarities are much greater than the differences. The large decrease in concept integration in this topic indicates that students do not make the connection of nucleophiles and electrophiles to acids and bases. Nucleophiles and electrophiles are viewed as new concepts that are isolated from other knowledge at this point in the students' understanding.

By the last topic of the semester, electrophilic addition, concept integration scores return to the level found at the beginning of the semester. This suggests that students have successfully integrated nucleophilic and electrophilic concepts in the time since the second topic. Experience using these concepts to explain reactions and suggest mechanisms may possibly assist students to integrate these further.

An alternative explanation for the decrease in concept integration in the second topic is the students' adjustment to learning new concepts in an active learning environment. By the end of the semester they may have adjusted to the demands put upon them during an active learning class versus a lecture class.

Except for the first topic, the concept integration measured by the second clicker question in each topic was the same or higher than the first measure on that topic. This may demonstrate increased understanding produced by a second activity on the topic, even though its content is more advanced. The identical second clicker questions were used as a delayed measure one week after completing the topic. The delayed measures were the same or better than that given the week before suggesting no loss of understanding.

The immediate clicker results show significantly higher concept integration than the delayed written examination questions. There are three possible explanations for this: (a) the
concept was not consolidated from short-term memory to long-term memory, (b) learning extinction during the time between the clicker and the hourly exam questions, or (c) the exam questions were more challenging than the clicker questions.

The clicker questions, although answered individually, were presented immediately after group discussion in class. This means that the concept was fresh in short-term memory which is easier to access than long-term memory and the students may have benefitted immediately from the group discussion. It may be that the concept was not fully consolidated in long-term memory and the higher clicker scores reflect short term learning. If the concept was fully consolidated into long-term memory, then the time between the clicker question and the hourly exam may have caused decay in memory. If either of these were the cause for the higher performance on the clicker questions then one would expect the one-week delay clicker question to show evidence of learning decay. However, this was not the case, and in fact the scores improved slightly on the short delay measure.

The third explanation, that the exam questions were more challenging than the clicker questions is probably the reason for the poorer performance on the exam questions. The degree of difficulty was probably not in the question content but in its format. For the clicker questions the student must analyze the question and identify all of the correct answers. For the written examination, the student must analyze the question, formulate the answer, and develop and communicate their individual reasoned argument. Facing a blank sheet a paper is a much more daunting task which requires additional processing skills and confidence than selecting an answer from a pre-made list. The critical thinking required for the type of question asked on the exams may be more difficult for a student.
Scores on the achievement questions were much better than the concept integration scores. This demonstrates that a student can perform well while not fully understanding a topic. This supports the argument that achievement is attained during the initial developmental learning stages that may precede conceptual understanding.

Second Research Question – Learning Approach Changes

Data Analysis

The pre-ASSIST survey was used to characterize the students’ initial learning approach to the course. Two questions were removed from the data due to questionable reliability, as explained in the previous chapter. The data in Table 20 compares the means of thirteen subcategories of learning approach. The maximum possible score for each learning approach subscale is 20. The lowest scores were in the surface subscales of lack of purpose and unrelated memorizing. The highest scores were in achieving and use of evidence.

Figure 18 compares the pre-ASSIST means for the three major categories for which the maximum possible score is 5. The means were 3.54 for deep approach, 3.52 for strategic approach, and 2.82 for surface approach. The omnibus test results for significance are shown in Table 21. Deep and strategic means were significantly larger than the surface approach mean, but not significantly different from each other.
Table 20

*Pre-Course Learning Approach Survey Means*

<table>
<thead>
<tr>
<th>Subscale</th>
<th>N</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeking meaning</td>
<td>98</td>
<td>14.52</td>
</tr>
<tr>
<td>Relating ideas</td>
<td>99</td>
<td>13.91</td>
</tr>
<tr>
<td>Use of evidence</td>
<td>101</td>
<td>15.23*</td>
</tr>
<tr>
<td>Interest in ideas</td>
<td>101</td>
<td>13.41*</td>
</tr>
<tr>
<td>Metacognition</td>
<td>99</td>
<td>14.75</td>
</tr>
<tr>
<td>Organized studying</td>
<td>98</td>
<td>14.06</td>
</tr>
<tr>
<td>Time management</td>
<td>98</td>
<td>14.27</td>
</tr>
<tr>
<td>Alertness to assessment demands</td>
<td>97</td>
<td>14.19</td>
</tr>
<tr>
<td>Achieving</td>
<td>100</td>
<td>15.39</td>
</tr>
<tr>
<td>Lack of purpose</td>
<td>101</td>
<td>9.58</td>
</tr>
<tr>
<td>Unrelated memorizing</td>
<td>98</td>
<td>11.26</td>
</tr>
<tr>
<td>Syllabus-boundness</td>
<td>95</td>
<td>12.55</td>
</tr>
<tr>
<td>Fear of failure</td>
<td>100</td>
<td>12.98</td>
</tr>
</tbody>
</table>

*Adjusted by removing questions 23 and 52 and recalculating means*

![Pre-course Learning Approaches](image)

*Figure 18. Comparison of pre-survey learning approach means*
Table 21

Statistical Comparisons of Pre-Course Learning Approaches (N=101)

<table>
<thead>
<tr>
<th>Pair</th>
<th>Approach</th>
<th>Mean Diff.</th>
<th>t</th>
<th>df</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1*</td>
<td>Mean Deep Approach &amp; Mean Strategic Approach Score</td>
<td>0.01</td>
<td>0.29</td>
<td>100</td>
<td>.000</td>
</tr>
<tr>
<td>Pair 2*</td>
<td>Mean Deep Approach &amp; Mean Apathetic Approach Scale</td>
<td>7.59</td>
<td>7.59</td>
<td>100</td>
<td>.001</td>
</tr>
<tr>
<td>Pair 3</td>
<td>Mean Strategic Approach Score &amp; Mean Apathetic Approach Scale</td>
<td>8.07</td>
<td>8.07</td>
<td>100</td>
<td>.401</td>
</tr>
</tbody>
</table>

*Significantly different at α = .05

The pre- and post- ASSIST survey data were analyzed to evaluate the impact of the course on students’ learning approaches. Statistical assumptions were tested prior to analysis to determine the appropriateness of a t-test. Descriptive statistics and histograms were evaluated for each of the pre and post surveys for three major categories and small deviations from a normal distribution were found. However, with larger sample sizes, the t-test is tolerant of minor violations of the normality assumption (Maxwell & Delaney, 2004; Pallant, 2001). Based on this, the t-test was used in this study.

Students who took the pre- and post- surveys were evaluated for differences in gender and ethnicity. Figure 19 shows the difference in the students who voluntarily completed the pre- and post- surveys. The gender and ethnicity distributions were proportionally different for the two surveys.
Since the proportions of the two gender groups and four ethnic group sizes were different in the pre- and post- surveys, the groups could not be compared because the basic assumptions in a factorial repeated-measure ANOVA would be violated. For this reason a paired $t$-test on the entire population was used. In order to obtain the most rigorously valid test results, missing data were treated listwise for this analysis rather than by variable, reducing the sample size from 250 to the set of 54 students who consented to be part of the study and completed both the pre and post survey in its entirety. By comparing the pre and post scores of the same students, a Within-Groups statistical analysis was performed improving the study validity. This avoided using the Between-Groups statistical analyses of literature studies in which different groups of students were compared reducing validity. The downside of the listwise treatment in this study is loss of power to detect changes that have actually occurred.

The paired $t$-test results for the pre and post ASSIST surveys are given in Table 22. This analysis tests the validity of the null hypothesis stated in the previous chapter: a student who completes one semester of guided inquiry organic in a large class will show no significant
differences in learning approach from the beginning to the end of the semester as measured by the ASSIST survey.

Table 22
Pre- and Post- Mean Differences in Paired t-Test of ASSIST Variables (N = 54, df = 53, p < .05)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean diff.</th>
<th>Std. dev.</th>
<th>t</th>
<th>p (2-tailed)</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep Approach</td>
<td>0.030</td>
<td>0.39</td>
<td>0.57</td>
<td>.573</td>
<td></td>
</tr>
<tr>
<td>Seeking Meaning</td>
<td>0.148</td>
<td>1.90</td>
<td>0.57</td>
<td>.569</td>
<td></td>
</tr>
<tr>
<td>Relating Ideas</td>
<td>0.352</td>
<td>2.08</td>
<td>1.25</td>
<td>.218</td>
<td></td>
</tr>
<tr>
<td>Use of Evidence</td>
<td>-0.019</td>
<td>1.83</td>
<td>-0.07</td>
<td>.941</td>
<td></td>
</tr>
<tr>
<td>Interest in Ideas</td>
<td>-0.037</td>
<td>2.05</td>
<td>-0.13</td>
<td>.895</td>
<td></td>
</tr>
<tr>
<td>Metacognition</td>
<td>0.093</td>
<td>2.28</td>
<td>0.30</td>
<td>.767</td>
<td></td>
</tr>
<tr>
<td>Strategic Approach</td>
<td>-0.002</td>
<td>0.35</td>
<td>-0.05</td>
<td>.961</td>
<td></td>
</tr>
<tr>
<td>Organized Studying</td>
<td>0.111</td>
<td>2.30</td>
<td>0.35</td>
<td>.724</td>
<td></td>
</tr>
<tr>
<td>Time Management</td>
<td>0.148</td>
<td>1.81</td>
<td>0.60</td>
<td>.549</td>
<td></td>
</tr>
<tr>
<td>Alertness to Assessment</td>
<td>-0.315</td>
<td>2.15</td>
<td>-1.07</td>
<td>.287</td>
<td></td>
</tr>
<tr>
<td>Achieving</td>
<td>0.0185</td>
<td>1.63</td>
<td>0.08</td>
<td>.934</td>
<td></td>
</tr>
<tr>
<td>Surface Approach</td>
<td>-0.123</td>
<td>0.33</td>
<td>-2.77</td>
<td>.008</td>
<td>.127</td>
</tr>
<tr>
<td>Lack of Purpose</td>
<td>-0.796</td>
<td>2.42</td>
<td>-2.42</td>
<td>.019</td>
<td>.099</td>
</tr>
<tr>
<td>Unrelated memorizing</td>
<td>-0.500</td>
<td>1.74</td>
<td>-2.12</td>
<td>.039</td>
<td>.079</td>
</tr>
<tr>
<td>Syllabus-boundness</td>
<td>-0.482</td>
<td>2.30</td>
<td>-1.54</td>
<td>.129</td>
<td></td>
</tr>
<tr>
<td>Fear of Failure</td>
<td>-0.185</td>
<td>2.36</td>
<td>-0.58</td>
<td>.566</td>
<td></td>
</tr>
</tbody>
</table>

The only statistically significant difference in these students on the three major approaches to learning was in the surface approach. The surface mean showed a decrease of 0.123 with t = -2.773, p = .008 at α = .05 and N = 54 from pre- to post-. This suggests that by the end of the course the average student demonstrated a lower surface approach to learning. Therefore the null hypothesis is rejected and there was a significant difference in learning approach over the semester as demonstrated by these statistical results.
Further inspection of Table 22, shows that two of the thirteen ASSIST survey subscales demonstrated a statistically significant decrease between the pre- and post- surveys means. The mean decrease for unrelated memorizing is 0.500, \( t = -2.118, p = .039 \), and the lack of purpose mean decrease was 0.796, \( t = -2.42, p = .019 \).

The questions that comprise the lack of purpose subscale are directed at the students’ belief that their study is “interesting”, “relevant” and “worthwhile”. The significant decrease in the lack of purpose scores over the semester suggests that students found more meaning and relevance in their study and believed their study was more worthwhile by the end of the course compared to what it was at the beginning.

The unrelated memorizing subscale is based on the ASSIST survey questions that ask the student how much their study “is unrelated bits and pieces”, “doesn’t make sense”, and if the student “is not sure what is important”, and “has trouble making sense of what I need to remember”. The significant decrease in unrelated memorizing scores during the semester suggests that students could both make more sense of their study and memorized less by the end of the course as compared to what they did at the start of the course.

The effect sizes, \( \eta^2 \), for the significantly different results – surface approach scale, lack of purpose subscale, and unrelated memorizing subscale – were calculated using the following formula:

\[
\eta^2 = \frac{t^2}{t^2 + (N-1)}
\]

The guidelines for interpreting effect sizes are small 0-5%, moderate 6-13%, and large >14% (Cohen, 1988).
The reduction in surface approach which has an effect size of 13%, falls in the higher moderate range. This reduction was a reflection of the decreases in the lack of purpose and unrelated memorizing subscales. The effect size for the lack of purpose subscale was 10% and for the unrelated memorizing subscale was 8%. Both effect sizes fall into the moderate range.

Discussion

These data do not demonstrate that the reduction of surface learning approach was caused by the class, only that there were statistically significant changes in the learning approaches of these 54 students. In order to infer that this particular pedagogy was responsible for the effect, the degree of learning approach changes in a lecture class would need to be compared to those of another pedagogy in another study.

The deep and strategic learning approaches have significantly higher means (3.5 of 4.0) than the surface approach (2.8 of 4.0). This indicates that these students in general are motivated to learn – or at least they think they are. It may be that the hard work of learning organic chemistry is not what they had in mind when they answered the survey. However, the active class did not seem to decrease their enthusiasm for learning as shown in the end of semester survey compared to the beginning of the semester survey. There was a moderate but significant reduction in student surface approach and perhaps a larger effect was not detected due to the cautious listwise treatment that reduced the power of the test. With increased numbers and statistical power, more changes might be detected. However, this study suggests that one semester of an active pedagogy using guided inquiry may reduce surface learning but it is not enough to make practical changes to students’ deep learning approach.
Third Research Question – Learning Approach Effects on Concept Integration

Data Analysis

A canonical correlation analysis (CCA) was conducted to explore the relationships of the student learning approaches with their learning success. The learning approach survey given at the beginning of the semester was used to create predictor variables for student learning success. The deep, strategic, and surface scores for each student were transformed into standard z-scores for this analysis. The criterion variables for student learning success were achievement and concept integration. These two variables were measured using the average concept integration score and average achievement score on both the three hourly topic exams and the final exam. The reasons for using the hourly and final exam scores were that they more accurately reflect long-term memory storage and the ability to synthesize a reasoned answer than the immediate and short delay multiple answer questions. Canonical correlation analysis evaluates the multivariate shared relationship between the two variable sets by generating a synthetic variable from the predictor variables and a second synthetic variable from the criterion variables. The correlation of the two synthetic variables is then evaluated.

Table 23

**Statistical Significance Test for the Full CCA Model: Within Cells Regression Multivariate Analysis**

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Value</th>
<th>F</th>
<th>Hypothesis df</th>
<th>Error df</th>
<th>Significance of F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilks’ Λ</td>
<td>.702</td>
<td>3.92</td>
<td>6</td>
<td>122</td>
<td>.001</td>
</tr>
</tbody>
</table>

Table 23 gives the results of the analysis that tests for validity of the null hypothesis for the research question, which is: There is no correlation between learning approach and either
concept integration or achievement for a student who completes one semester of guided inquiry organic chemistry in a large class.

The full model was statistically significant, with a Wilks’ $\Lambda$ of .702, and $F = 3.92$ (6, 122), $p = .001$, thus the null hypothesis for this research question is rejected. Wilks’ $\Lambda$ represents the portion of variance not explained in the model, so $1 - \Lambda$ is the effect size, which for the entire model is .298 or 30%. The two squared canonical correlations ($R_c^2$) for each of the two functions produced by the analysis were .267 and .042 as shown in Table 24. The first $R_c^2$ represents approximately 27% effect size, which is the bulk of the overall 30% effect size. This means that 27% of the variance in one set of variables overlaps with the variance in the other set of variables. This function was explored further because of its larger effect size.

Table 24

<table>
<thead>
<tr>
<th>Root No.</th>
<th>Eigenvalue</th>
<th>%</th>
<th>Cumulative %</th>
<th>Canonical Correlation</th>
<th>$R_c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.36</td>
<td>89.29</td>
<td>89.29</td>
<td>0.517</td>
<td>0.267</td>
</tr>
<tr>
<td>2</td>
<td>0.04</td>
<td>10.71</td>
<td>100.00</td>
<td>0.205</td>
<td>0.042</td>
</tr>
</tbody>
</table>

The second function’s $R_c^2$ represents a very small effect size, only a 4% overlap of the residual variance after the first correlation. In addition the dimension reduction analysis for the second function, shown in Table 25, demonstrated that, by itself, it was not statistically significant, $F = 1.36$ (2,62), $p = 0.266$. For these two reasons the second function was deemed too small to have any importance and was not investigated further.
The univariate correlation and omnibus tests for the criterion variables, achievement and concept integration are given in Table 26. Both the average exam concept integration and the average exam achievement scores are significantly correlated to the rest of the model. Concept integration contributes 23% to the overall model where as achievement contributes half as much with 12%.

Table 26

<table>
<thead>
<tr>
<th>Variable</th>
<th>$r^2$</th>
<th>adjusted $r^2$</th>
<th>$F$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept Integration</td>
<td>.263</td>
<td>.227</td>
<td>7.39</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Achievement</td>
<td>.160</td>
<td>.119</td>
<td>3.94</td>
<td>.012</td>
</tr>
</tbody>
</table>

$\alpha = .05$, df (3, 62), $N = 66$

The standardized canonical coefficients (weights), the correlations (structure coefficients), and their squared structure coefficients for the first function, are given in Table 27. The structure coefficients represent the contribution each variable makes to its synthetic variable, and its square represents the effect size. For the criterion variable, the squared
structure coefficients, $R_c^2$, for concept integration has a value of 0.984 and for achievement 0.526. This indicates that 98% of the variance overlap of the two synthetic variables is associated with concept integration and 53% is associated with achievement. Since achievement and concept integration are correlated to each other, they can each explain some of the

Table 27

*Coefficients for Criterion Variables and Predictor Variables for the First Function*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Canonical coefficient</th>
<th>Structure coefficient</th>
<th>$R_c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Criterion Variables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concept Integration</td>
<td>1.166</td>
<td>0.992</td>
<td>.984</td>
</tr>
<tr>
<td>Concept Achievement</td>
<td>-0.210</td>
<td>0.725</td>
<td>.526</td>
</tr>
<tr>
<td><strong>Predictor Variables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep Approach</td>
<td>0.158</td>
<td>0.480</td>
<td>.230</td>
</tr>
<tr>
<td>Strategic Approach</td>
<td>0.097</td>
<td>0.293</td>
<td>.086</td>
</tr>
<tr>
<td>Surface Approach</td>
<td>-0.917</td>
<td>-0.976</td>
<td>.953</td>
</tr>
</tbody>
</table>

For the predictor variable, student learning approach, the squared structure coefficient for deep approach was 0.230, strategic approach was 0.086, and surface approach was 0.953, as shown in Table 27. Thus the deep approach explains 23% of the overlap variance, the strategic approach 9%, and the surface approach 95%. It is important to note that the correlation for the surface approach is negative, indicating an inverse relationship to the rest of the model, whereas the deep and strategic approaches are a direct correlation.
Discussion

For the criterion variable the written free response exam scores were used for this analysis, and clicker scores were not included. The written question may more accurately reflect students’ ability to synthesize a reasoned answer. The clicker questions do require critical analysis; students only need to identify all the correct answers already formulated for them. As discussed earlier, the written examination required not only the critical analysis, but also formulation and communication of an individually reasoned answer.

For the predictor variable the pre- ASSIST survey scores were used because it was assumed they reflected the student’s preferred learning approach during a majority of the study.

The variance overlap between the predictor variable, learning approach, and the criterion variable, successful academic performance, is 30%. The thirty percent variance overlap between the two synthetic variables can be analyzed further to see how much can be explained by each of the criterion and predictor component variables.

For the criterion variable 53% of the variance overlap was associated with academic achievement, but 98% was associated with concept integration. So student learning approach predicts concept integration nearly twice as well as it predicts achievement. Since achievement is correlated with concept integration it is not unexpected that they explain some of the same variance.

Student learning approach predicts concept integration success twice as well as achievement success. Of the learning approach variables, surface is the best predictor of success, albeit a negative one – the higher the surface learning score, the lower the
achievement and concept integration scores. The surface approach explains 95% of the variance overlap with the student test scores. The deep approach can explain 23% of the variance overlap but the strategic approach only explains 9%.

Combining these two canonical variables – learning approach and achievement/concept integration – we can state that a high surface learning approach (95% of overlap) has a strong correlation to weak concept integration (98% of overlap). The deep learning approach does predict successful concept integration, but far less effectively than surface approach predicts poor integration. A possible explanation for this is that the some students report themselves as deep learners when in fact they are surface learners; they may not want to admit it to themselves or others.

Summary

Statistical analyses were completed to answer the three research questions. The first question asked if student achievement and concept integration significantly changed during the time over which a topic was studied, and if there was a significant change across the three topics. Analysis using Repeated Measures MANOVA produced significant results for both achievement and concept integration. Additionally there were significant changes within topics, across topics, and for the interaction of across and within topic for both achievement and concept integration.

For across topics there was a significant difference for both achievement and concept – a 67% effect size for achievement and 77% effect size for concept integration. Pairwise analysis demonstrated that for both achievement and concept integration the second topic, nucleophilic substitution, was significantly lower than the first, acid/base, or the third,
electrophilic addition. However, the first and third topics were not different from each other for either achievement or concept integration. Thus nucleophilic substitution questions were more challenging for students for both achievement and conceptual understanding.

Within topics achievement increased significantly with each average successive measure within a topic with an effect size of 34%. All measures were significantly different from each other in terms of achievement. Within topics concept integration was also significant with an effect size of 34%. However, unlike achievement, there was no significant change in concept integration between clicker questions, only between clicker questions and the hourly exams. The average concept integration scores significantly decreased on the hourly exams compared to the clicker questions. There was an interaction effect between across topics and within topics for both achievement and concept integration. The interaction effect for achievement was 77% and for concept integration 46%.

The second research question asked if changes in student learning approach would be observed after a one semester guided inquiry class. Both at the beginning and end of the semester the surface learning approach was significantly less than the deep or strategic learning approach in the average student. However, there was no significant difference between the deep and strategic approach. A paired t-test of pre and post- survey responses demonstrated significant change in one of the three approaches but not the other two. The surface approach decreased over the semester, in the same students with an effect size of 13%. The decrease was primarily due to the significant reductions in the unrelated memorizing and lack of purpose subscales.
The third research question addressed the relationship of achievement and concept integration with the three learning approaches – deep, strategic and surface. A canonical correlation analysis was conducted to compare a synthetic predictor variable composed of the three learning approaches and a synthetic criterion variable composed of achievement and concept integration. There was a 30% overlap in variance between the criterion and predictor variables. Each of the predictor variables contributed differently to the overlap; the surface approach accounted for 95% of the overlap, the deep approach 23%, and the strategic approach 9%. The criterion variables also contributed differently to the overlap—achievement explained 53% of the variance overlap and concept integration 98%. Thus for the 59 students analyzed these variables are correlated with the largest correlation being a negative relationship of surface learning and concept integration. Surface learning is the best predictor of the three for both achievement and concept integration; however it is twice as successful in predicting poor concept integration.
CHAPTER V

CONCLUSION

In today’s global community with finger tip access to massive amounts of information, the goal of education should be teaching our students to think critically and apply information in novel situations. Do our students learn meaningfully? If not, is it because of the way we teach or the way students approach learning? The answers to these questions can inform educators on ways to move instruction toward the goal.

The relationship of the student learning approach and their cognitive development was investigated in this study. Students’ success with higher and lower cognitive tasks was measured during the first semester of a guided inquiry organic chemistry large lecture class. Lower cognitive development was measured as achievement, in the forms of algorithmic problem solving, pattern recognition, or memorization; and higher cognitive development was measured as concept integration, demonstrated by explaining, applying, and relating concepts. Lower cognitive tasks, achievement, reflect the first two stages of development of learning, and higher cognitive tasks, concept integration provide evidence of the third and fourth developmental stage. The fifth stage, which is expert, was not measured.

The study was performed in an uncommon learning environment designed to promote deep, meaningful learning. A class section of 250 students was taught using Process Oriented Guided Inquiry Learning (POGIL) — a student-centered active learning pedagogy that incorporates guided inquiry in-class activities to promote conceptual understanding as well as achievement. This learning environment attempts to foster deep, meaningful learning and reduce memorization and algorithmic problem solving (Moog & Farrell, 1997). The activities
were based on a learning cycle, based on both the way the brain learns and the scientific process in phases of exploration, concept invention or term introduction, and conceptual expansion or application (Lawson, 2003). This active pedagogy is theoretically based, using theories from cognitive psychology, neurobiology, and educational psychology, including Piaget, Vygotsky, and Ausubel. Modifications to the POGIL pedagogy were made to accommodate the large class environment. Clickers were used to provide the instructor immediate feedback during the learning process allowing her to detect misconceptions so that they could be addressed immediately and then allowing students to reflect on what they have just learned. Performing the study in this learning environment maximized the emphasis placed on deep learning in a large classroom versus a passive lecture environment. Even though teaching for depth takes more time, the class “covered” the same course content as the parallel traditionally taught lecture sections.

To determine the depth of students’ learning over the semester, achievement and concept integration were measured over three topics during the semester that related the concepts of electron densities and electron pair energies. The three topics were acid/base, nucleophilic substitution and electrophilic addition reactions. The results of this part of the study demonstrated that students, at the beginning of the course, were in the second and third developmental stages for acid and base concepts, extending their existing knowledge of acids and bases from general chemistry to organic compounds. The students ended the semester at the achievement and concept integration for electrophilic addition as they had with acid and bases at the beginning of the semester, demonstrating the same stage of development (Briggs et al., 2006). However, in the middle of the semester their achievement dropped. The MANOVA
analysis shows that student achievement for the second topic, nucleophilic substitution, dropped significantly, and concept integration was very low compared to that of the topics taught at the beginning and end of the semester.

It is possible that students performed better on acid/base reactions than on nucleophilic substitution reactions because they had prior knowledge of acids and bases from second semester general chemistry on which to build their conceptual network. In the nucleophilic substitution topic, the students did have previous experience with mechanistic writing with free radical reactions, but no experience with nucleophiles and electrophiles. Perhaps nucleophilic substitution was more challenging for them because this was the first time they encountered nucleophiles and electrophiles so they could only acquire the concept in isolation through rote memorization. Students may have needed more time and experience to make connections between nucleophile and base concepts. Achievement on the third topic, electrophilic addition, may have increased because by then students had experience with both mechanistic language and nucleophiles and electrophiles in different contexts. This “spiral learning” experience may have contributed to students’ schema development of nucleophiles and electrophiles. It may be that if the two topics of nucleophilic substitution and electrophilic addition were switched, students would have more difficulty with electrophilic addition because it would have been the first context in which they encountered nucleophilic and electrophilic concepts. In fact, some organic chemistry textbooks do reverse this order; however this study was not able to differentiate the topic difficulty versus its placement in the semester.
Students in this class progressed through two of the three phases of learning. When students first encountered the concepts of nucleophiles and electrophiles in the nucleophilic substitution topic, they utilized verbatim learning, as evidenced by their ability to answer achievement questions but inability to explain the underlying concepts. However, students’ concept integration scores improved on their last topic, electrophilic addition, after experience using these concepts in different contexts for other topics. This additional experience enabled students to develop more complete schema which improved their ability to explain and apply these concepts in new situations. Although students were successful in schema development of acids, bases, nucleophiles, and electrophiles in this class, the average student was not able to connect these at more general and theoretical level of electron densities, which is a more advanced stage. This finding supports the three phases of learning proposed by Shuell (1990): (a) rote memorization, (b) schema development and (c) generalization to theory.

Both achievement and concept integration were significantly lower on the written, free response questions on the hourly exams, than in the in-class multiple answer clicker questions. It is possible that the exam questions were more challenging or contained more concepts than the clicker questions, or that the lower performance was a reflection of test anxiety. However, an important difference between in-class questions and exam questions was format. In the multiple answer format the students were required to critically analyze the problem and identify all the correct answers from a list, whereas, for a written free response question the students were not only required to analyze and solve the problem, but to also formulate and successfully communicate a reasoned answer. In the case of achievement questions students have been required to draw arrows rather than identifying a correctly drawn mechanism. The
concept integration scores were lower than the achievement scores on the hourly exams because it is even more challenging for students to communicate conceptual relationships in essay form rather than using an algorithm to answer a free response achievement problem.

This study suggests that alternative grading of carefully written, conceptual, free response questions may yield more information on students’ knowledge and their conceptual connections or misconceptions than objective questions. If assessment for meaningful learning is desired, then requesting explanations of concepts, linking them to other concepts, and applying them in novel situations may be a more valid method of assessment.

Clickers played a role in large class active instruction by providing the instructor and students immediate feedback during the learning process allowing students to correct and reflect on misconceptions during the concept integration process. However, clickers were not a good assessment of long-term memory consolidation or a student’s ability to construct and communicate a reasoned answer to critical thinking question.

The students’ performance on achievement questions was higher than on concept integration questions, especially on written exams. Often students who successfully answered achievement questions could not answer the conceptual questions. This study’s findings suggest that students can experience success on achievement questions without having conceptual understanding. Therefore solving algorithmic problems is not necessarily evidence of deep, meaningful learning on the part of the student. This finding supports findings provided in the literature for organic chemistry (Bhattacharyya & Bodner, 2005) and for general chemistry (D. M. Bunce et al., 1991; Gabel et al., 1984; Herron & Greenbowe, 1986; Nurrenbern & Pickering, 1987). Since deep learning requires more time, the deep learning in this class may
have been negatively impacted by the large amount of material required in the organic chemistry course. In between the activities students needed to memorize reagents and reactions conditions, as in the parallel lecture sections. This heavy workload may have interfered with the student’s ability to focus on meaningful concepts and the depth of learning provided by the guided inquiry activities. A mixed message may have been sent to organic chemistry students – learning deeply and meaningfully is important, but assessment will also be based on a large amount of memorized material. The organic chemistry curriculum is large and if students are to be able to retain and apply the basic concepts of organic chemistry the breadth should be reduced and more focus placed on depth of learning. Most students who take organic are biology, pre-med or pre-pharmacy majors. It would be an advantage to these students to learn to think scientifically and inductively. Perhaps that should be one of the goals of the organic course; and in many minds it is.

**Student Learning Approach**

Students come to a course with a preferred learning approach that is based on their definition of knowledge and learning. Their learning approach may be driven by a desire for deep meaningful understanding, achievement in the course, or just passing the course. Students may prefer a deep approach, a strategic approach, or a surface approach, but often depending on the environment, a combination of the three is most successful (Entwistle & Ramsden, 1983).

To determine if the students’ approach to learning changes after a one semester experience in a large class organic chemistry using guided-inquiry, learning approach was measured using the pre and post-ASSIST survey. This study found a significant decrease in the
average student’s surface approach over the semester with an effect size of 12%, but no significant change in the average student’s preference for the deep or strategic approaches. The decrease in surface approach was attributed to changes in students’ answers regarding “lack of purpose” and “unrelated memorizing” in their studies. The same students reported at the end of the semester that they had a greater sense of purpose, meaning and relevance in their learning. However, these results do not establish a causal relationship between the active guided inquiry pedagogy and the changes in learning approach because there was no control group with which to compare these students.

This study’s findings support some findings reported in the literature (Richardson, 2005; Sadlo & Richardson, 2003), and partially support others (Kember et al., 1997) which demonstrate that students’ learning approach is malleable. This study’s findings also refute those of others who found no significant change in learning approach or an increase in surface approach in classes where deep learning was emphasized by pedagogy and instruction (Donn, 1990; Scouller & Prosser, 1994). However, these studies explained their findings by suggesting that, in spite of the pedagogy, deep learning was discouraged and surface learning was encouraged by the objective testing on which students’ grades were based. Additional studies demonstrate that students who take a surface approach to learning often score better on objective examinations than those that try to learn meaningfully. However, those students with a deep approach perform better on free response, critical thinking and essay questions (Novak & Gowin, 1984; Scouller, 1998). These later studies used similar methods of measuring student outcomes as those in this study. The mixed findings in all these studies may be
confounded by different assessment methods, Between Group study design and different disciplines.

This study found a 30% correlation between learning approach and learning development stage. The relationship of student learning development stage and their learning approach was analyzed through correlation of achievement and concept integration with deep, strategic, and surface learning approaches. The contribution of strategic approach to this correlation was minimal; whereas the deep approach positively contributed 23% to the correlation and surface approach negatively contributed 95% to the correlation. This finding demonstrates that the deep approach is a predictor of successful achievement and concept integration, and a surface approach is an even better predictor of failure to learn meaningfully. This finding is in agreement with Ramsden’s (1992) findings using qualitative measures.

Achievement contributed 53% and concept integration contributed 98% to the correlation with learning approach. This means that the student's learning approach has a good correlation with achievement, but a much stronger correlation with concept integration. This finding supports the idea that some achievement is possible with a surface approach, but concept integration, requiring higher cognitive skills, will not occur with a surface approach. A student who chooses to adopt a surface approach will not learn deeply or meaningfully. This supports Novak’s findings (1984).

If the desired goal of education is achievement, a surface learning approach and verbatim learning can mean success for students. However, if the desired goal of education is meaningful understanding, feedback between instructors and students during the learning process is important to make the conceptual connections that permit deep learning. This
feedback enables detection of misconceptions so that they can be addressed immediately and allows students to reflect on what they have just put in short term memory. However, clickers are not a valid assessment of long-term memory consolidation or a student’s ability to construct and communicate a reasoned answer to critical thinking question. Students may be able to critically evaluate the selection of answers to a clicker question, but not be able to formulate their own argument on a blank piece of paper.

Grading free response questions for full explanation of linked concepts may yield further information on students’ ideas and their conceptual connections or misconceptions. If assessment is used in a formative way – as a learning experience – seeking connections between concepts may be a reasonable and practical grading rubric for carefully written free response questions.

Limitations of Study and Recommended Further Research

The results of this study cannot be generalized to other classes due to the unique learning environment. A causal relationship cannot be established because there was no control group used in this study. Future studies may be able to compare concept integration of different pedagogies, but that was not the intent of this study.

Since surface learning is a strong predictor of failure to learn meaningfully it would be an important area for future research. What can influence surface learners to deepen their approach during the course of a semester? Knowing how to positively influence the depth of students’ learning approach could produce more meaningfully learning in these students. Are students’ learning approaches a result of the first twelve years of education that rewards rapid, surface achievement? If the influence of the K-12 years is significant, then educational goals
that are addressed in those years may positively impact learning in a university environment. What can educators do to facilitate and effect change in how students appreciate the learning process? Instructors need to know specifically what instructional approaches can change students’ view of what learning is and which approaches are not helpful.

Since meaningful learning and conceptual understanding are more challenging to most chemistry students than achievement, further investigations in this area would be beneficial. What can chemical educators do to facilitate meaningful learning? Knowing what instructional approaches work best based on research findings can motivate change in the classroom. Is the vast content in the organic chemistry course a factor? Are we sending mixed messages to our students by requiring verbatim memorization of large amounts of material while asking them to understand and apply the basic principles of chemistry? If volume of content promotes rote learning then we need to reduce the amount of curriculum to enable the time required for deeper understanding. Would a reorganization of the organic chemistry curriculum around basic principles be more effective for meaningful learning than the current functional group organization? This is the question asked by the ACS Organic Chemistry Curriculum Committee in 1972, but still has not been answered with research. If we are to effect meaningful change in the classroom all of these are questions worth answering.
APPENDIX A

IRB APPROVALS AND STUDENT CONSENT FORM
August 26, 2008

Christina Mewhinney
Department of Chemistry
University of North Texas

Re: Human Subjects Application No. 08284

Dear Ms. Mewhinney,

As permitted by federal law and regulations governing the use of human subjects in research projects (45 CFR 46), the UNT Institutional Review Board has reviewed your proposed project titled "Student Success in Large Class Organic Chemistry." The risks inherent in this research are minimal, and the potential benefits to the subject outweigh those risks. The submitted protocol is hereby approved for the use of human subjects in this study. Federal Policy 45 CFR 46.109(e) stipulates that IRB approval is for one year only, August 26, 2008 to August 25, 2009.

It is your responsibility according to U.S. Department of Health and Human Services regulations to submit annual and terminal progress reports to the IRB for this project. Please mark your calendar accordingly. The IRB must also review this project prior to any modifications.

Please contact Sheila Boams, Research Compliance Administrator, or Boyd Hennecor, Director of Research Compliance, at extension 3940, if you wish to make changes or need additional information.

Sincerely,

[Signature]
Kenneth W. Sewell, Ph.D.
Chair
Institutional Review Board

KS: sb

CC: Dr. Diana Mason
DATE: July 29, 2008

TO: Suzanne Ruden, PhD
Department of Chemistry
Box 842006

FROM: Lee Ann Hansen, PharmD
Chairperson, VCU IRB Panel D
Box 940568

RE: VCU IRB # RM11706
Title: Student Success in Large Class Organic Chemistry

On July 23, 2008, the following research study was approved by expedited review according to 45 CFR 46.110 Categories 6 and 7. This approval reflects the revisions received in the Office of Research Subjects Protection on July 23, 2008. This approval includes the following items reviewed by this Panel:

PROTOCOL: Student Success in Large Class Organic Chemistry
- Research Plan (Dated 16 June 2008; received in ORSP 7/23/08)

CONSENT/ASSENT:
- Research Subject Information and Consent Form (Version 1-11-08; dated 7/23/2008; 1 page; received in ORSP 7/23/08)

ADDITIONAL DOCUMENTS:
- Approaches and Study Skills Inventory for Students (aSSISI) (Version 1, July 24, 2008; received in ORSP 7/23/08)
- Metacognitive Activities Inventory (MCA-1) (Version 1, July 24, 2008; received in ORSP 7/23/08)

This approval expires on June 23, 2009. Federal Regulations/VCU Policy and Procedures require continuing review prior to continuation of approval past that date. Continuing Review report forms will be mailed to you prior to the scheduled review.

The Primary Reviewer assigned to your research study is Ranjodh Gill, MD. If you have any questions, please contact Dr. Gill at rdgill@vcuhealth.vcu.edu or 828-5523, or you may contact Aleksandra Baldwin, IRB Coordinator, VCU Office of Research Subjects Protection, at abaldwin@vcu.edu or 827-1445.

Attachment – Conditions of Approval
Conditions of Approval:

In order to comply with federal regulations, industry standards, and the terms of this approval, the investigator must (as applicable):

1. Conduct the research as described in and required by the Protocol.

2. Obtain informed consent from all subjects without coercion or undue influence, and provide the potential subject sufficient opportunity to consider whether or not to participate (unless Waiver of Consent is specifically approved or research is exempt).

3. Document informed consent using only the most recently dated consent form bearing the VCU IRB “APPROVED” stamp (unless Waiver of Consent is specifically approved).

4. Provide non-English speaking patients with a translation of the approved Consent Form in the research participant’s first language. The Panel must approve the translated version.

5. Obtain prior approval from VCU IRB before implementing any changes whatsoever in the approved protocol or consent form, unless such changes are necessary to protect the safety of human research participants (e.g., permanent/temporary change of PI, addition of performance collaboration sites, request to include newly identified participants or participants that are wards of the state, addition/demotion of participant groups, etc.). Any disparate from these approved documents must be reported to the VCU IRB immediately as an Unexpected Problem (see §7).

6. Monitor all problems (anticipated and unanticipated) associated with risk to research participants or others.

7. Report Unanticipated Problems (UIPs), including protocol deviations, following the VCU IRB requirements and timelines detailed in VCU IRB WIP V8-08.

8. Obtain prior approval from the VCU IRB before use of any advertisements or other material for recruitment of research participants.

9. Promptly report and/or respond to all inquiries by the VCU IRB concerning the conduct of the approved research when or requested.

10. All protocols that administer any medical treatment to human research participants must have an emergency preparedness plan. Please refer to VCU guidance on http://www.research.vcu.edu/irb/guidance.htm.

11. The VCU IRBs operate under the regulatory authorities as described within:
   a) U.S. Department of Health and Human Services Title 45 CFR 46, Subparts A, B, C, and D (for all research, irrespective of source of funding) and related guidance documents.
   b) U.S. Food and Drug Administration Chapter 1 of Title 21 CFR 50 and 56 (for FDA regulated research only) and related guidance documents.
   c) Commonwealth of Virginia Code of Virginia, 32.1 Chapter 2.1 Human Research (for all research).
RESEARCH SUBJECT INFORMATION AND CONSENT FORM

TITLE:
STUDENT SUCCESS IN LARGE CLASS ORGANIC CHEMISTRY.

VCU REE NO.: #M11706

SPONSOR: Fund for the Improvement of Postsecondary Education (FIPSE) DUE 5 P11680800026

Before agreeing to participate in this research study, it is important that you read and understand the following explanation of the purpose and benefits of the study and how it will be conducted. If you do not understand something on this form please ask the study staff for an explanation. You may have an unsigned copy to take with you.

PURPOSE OF THE STUDY
The purpose of this research study is to discover more about how students learn Organic Chemistry in large classes and what tools help them succeed in the course.

You are being asked to participate in this study because you are taking a large Organic class that uses specific teaching tools that have been demonstrated to be helpful in learning.

DESCRIPTION OF THE STUDY AND YOUR INVOLVEMENT
If you decide to be in this research study, you will be asked to sign this consent form after any questions you may have are answered.

Your entire class of about 250 students is included in this study. Your responses to questions about organic chemistry and your understanding of class will be used to follow your learning of chemistry concepts. These responses will be in the form of normal in class work - either questions, quiz questions, and test questions. Outside the classroom, you will be asked to complete two online surveys about how you study and solve problems which will take about twenty to thirty minutes. Approximately four student groups will be videotaped during class discussing chemistry.

RISKS AND DISCOMFORTS
No foreseeable risks are involved in this project.

BENEFITS TO YOU AND OTHERS
We expect the project to benefit you by having a greater awareness of how you study science. It is hoped that your experiences in this class will benefit your study strategies in future science courses. The information we gain from this study may help us design more effective tools for learning in science courses.

APPROVED

[Signature]

11-11-08

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COSTS
There are no costs for participating in this study other than the time you will spend in the groups and filling out two online questionnaires that will take about 30 minutes.

CONFIDENTIALITY
Results are anonymous. Your data will be cross-referenced in the database by a code number, not your name. Potentially identifiable information about you will consist of your responses to a learning approach survey, a problem solving survey, quiz, test and clicker questions, and your final grade. Data is being collected only for research purposes and will be stored separately in a locked research area. Access to all data will be limited to study personnel and these records will be deleted in three years.

We will not tell anyone the responses you give us; however, information from the study and the consent form signed by you may be looked at or copied for research purposes by the sponsor of the research, or by Virginia Commonwealth University. Generalized results from this study may be presented at meetings or published in papers and a dissertation but your name will never be used in these presentations or papers.

With their permission, a few students will be videotaped working in groups in the classroom. The tapes and the notes will be stored in a locked cabinet. No names will be used in the tape transcription. After the information from the tape is typed up, the tapes will be destroyed.

Initial the box if you agree.

I agree to be video taped during class time. I understand that his video tape will have no influence on my grade. Video tapes will be kept locked until the study is completed and will be destroyed after the project is complete.

VOLUNTARY PARTICIPATION AND WITHDRAWAL
You do not have to take part in this opportunity and your refusal to participate or your decision to not participate will involve no penalty or loss of rights or benefits. Your decision whether to participate or to withdraw later will have no affect on your course grade. You may also choose not to answer particular questions that are asked in the study.

QUESTIONS
In the future, you may have questions about your participation in this study. If you have any questions, complaints, or concerns about the research, contact:

Dr. Suzanne Rader
Department of Chemistry
1001 West Main St
PO Box 842006
Richmond, VA 23284-2006
Telephone: 804-828-7519
Email: srazer@vcu.edu

APPROVED
7/23/05 SRLAB

5/30/2006 2
If you have any questions about your rights as a participant in this study, you may contact:

Office for Research
Virginia Commonwealth University
800 East Leigh Street, Suite 113
P.O. Box 980568
Richmond, VA 23298
Telephone: 804-827-2157

You may also contact this number for general questions, concerns or complaints about the research. Please call this number if you cannot reach the research team or wish to talk to someone else. Additional information about participation in research studies can be found at http://www.research.vcu.edu/irb/volunteers.htm.

CONSENT
I have read this consent form and my questions have been answered. I know the possible benefits and the potential risks and/or discomforts of the project. I understand that I do not have to take part in this opportunity and my decision to not participate will involve no penalty or loss of rights or benefits. My decision whether to participate or to withdraw later will have no effect on my course grade. I understand why the project is being conducted and how it will be performed. I understand my rights as a participant and I voluntarily consent to participate in this project by your signature on this consent notice.

Participant name printed ________________________________  Participant signature ______ Date____

Dr. Suzanne Rufer
Name of Person Conducting Informed Consent
Discussion / Witnesses
(Printed)

Signature of Person Conducting Informed Consent ____________ Date ______
Discussion / Witnesses

Same
Investigator Signature (if different from above) __________________________ Date ______

APPROVED

Timley Buiar

3-11-08

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APPENDIX B

CLASS ACTIVITY SCHEDULE
CHEM301 Fall 2008 Organic Chemistry 1

Activity # / Title

1: Resonance Structures
2: Drawing Organic Structures
3A: Acids/Bases and pKa Values
3B: Predicting pKa Strength without pKa Values
4: Nomenclature of Alkanes
5A: Conformation of Alkanes, acyclic alkanes
5B: Conformation of Alkanes, cyclohexane compounds
6: Radical Halogenation Reactions
7: Stereochemistry
8: Fischer Projections
9A: Substitution Nucleophilic, Bimolecular SN2
9B: Substitution Nucleophilic, Unimolecular SN1
10: Stereochemistry of E2 Elimination
11: Electrophilic Addition
12A: Electrophilic Addition, addition of oxygen
12B: Electrophilic Addition, addition involving cyclic intermediates or products
12C: Electrophilic Addition to alkynes
APPENDIX C

CONSTRUCT MAPS
Construct for First Acid/Base Activity (Instructor’s Activity 3A): pKa

 Concepts: Review Brønsted – Lowry acids and bases, relative strengths, equilibria positions, and equilibrium constants.

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Description</th>
<th>Constructs</th>
</tr>
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</table>
| I                   | Expected Prior Knowledge | ID Brønsted-Lowery acids and bases  
Determine acid strength from pKa |
| II                  | Common Misconception that gives wrong answer | Does not understand relationship of Ka and pKa  
Draws arrows for proton movement rather than electrons  
Confusion over conjugate pairs  
Confusion between acid and base |
| III                 | Basic understanding except for one new concept | Full integration of topic excepts makes error with one of the following: equilibrium position, curved arrows, predicting product |
| IV                  | Full Integration of current topic | Predict products of acid- base reaction (B/L)  
Predict relative equilibrium position  
Predict relative pKa of acid based on pKa of substances it reacts with  
Draw curved arrows for mechanism of acid base (B/L) reactions |
Construct for Second Acid/Base Activity (Instructor’s Activity 3B): Predicting Acid Strength without pKa Values

Concepts: The effects of formal charge, electronegativity, resonance, polarizability, and inductive effects have on acid strength and base stability.

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Description</th>
<th>Constructs</th>
</tr>
</thead>
</table>
| I                   | Expected Prior Knowledge | Predict products of acid-base reaction (B/L)  
Predict equilibrium position  
Predict relative pKa of acid based on pKa of substances it reacts with  
Draw curved arrows for mechanism of acid base (B/L) reactions |
| II                  | Common Misconception that gives wrong answer | Confuse electronegativity effect with inductive effect (not looking at atom bonded to hydrogen)  
Use electronegativity instead of polarizability to rank (example HI is weak and HF is strong) |
| III                 | Basic understanding except for one new concept | Predict and / or rank acid or base strength (bases more difficult) and EXPLAIN with one error on one of the following:  
Formal charge, electronegativity, resonance, inductive effects, and polarizability |
| IV                  | Full Integration of current topic | Understanding of acid or base strength (bases more difficult) based on:  
Formal charge, electronegativity, resonance, inductive effects, and polarizability |

Construct for Nucleophilic Substitution First Activity (Instructor’s Activity 9A) – Bimolecular Nucleophilic Substitution
Concepts: Reaction mechanism for concerted nucleophilic substitution reactions, reaction stereochemistry, nucleophilic strength, leaving group strength, transition state and energy relationships.

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Description</th>
<th>Constructs</th>
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</table>
| I                   | Expected Prior Knowledge | What constitutes a Lewis base  
Relationship of pKa to base strength  
Symbolism of curved arrow notation  
Concept of bond polarization and its relation to bond strength  
Concept of enantiomers  
General potential energy diagrams and transition state |
| II                  | Common Misconception that gives wrong answer | Understands what a substitution reaction is and  
Can identify specific reactions as substitution  
Can draw mechanism for S_n2 reaction but cannot EXPLAIN what the arrows mean  
Understands how the energy diagram relates to mechanism |
| III                 | Basic understanding except for one new concept | Explain that the arrows mean movement of electrons  
Connects concepts of acid-base theory to nucleophiles and leaving groups  
Can identify nucleophiles / leaving groups but cannot differentiate between weak and strong nucleophiles or good/ poor leaving groups  
Can predict correct stereochemistry but cannot use transition state to explain why. |
| IV                  | Full Integration of current topic | Understands how rear attack causes inversion of product and can predict correct stereochemistry  
Understands weak vs. strong nucleophiles and can differentiate between them  
Understands good vs. poor leaving groups and can differentiate between them  
Understands the kinetics, thermodynamics and transition state of mechanism |
Construct for Nucleophilic Substitution Second Activity (Instructor’s Activity 9B) – Unimolecular Nucleophilic Substitution

Concepts: Reaction mechanism for two step nucleophilic substitution reactions, product stereochemistry, rearrangements

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Description</th>
<th>Constructs</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Expected Prior Knowledge</td>
<td>Carbocation structure and hybridization affects shape and stability</td>
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<tr>
<td></td>
<td></td>
<td>Knows what a substitution reaction is and can identify specific reactions</td>
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<td></td>
<td>Understands the concept of potential energy diagrams</td>
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<td></td>
<td></td>
<td>Knows in general that reaction rate depends on concentration of species</td>
</tr>
<tr>
<td>II</td>
<td>Common Misconception that gives wrong answer</td>
<td>Can predict the product of a substitution reaction and draw mechanism for</td>
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<td></td>
<td></td>
<td>$\text{S}_{\text{n1}}$ reaction but cannot explain what the arrows mean</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can identify roles of reagents as nucleophiles and electrophiles but not</td>
</tr>
<tr>
<td></td>
<td></td>
<td>differentiate strength between two nucleophiles or electrophiles</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can identify species in energy diagram but cannot explain their energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>differences</td>
</tr>
<tr>
<td>III</td>
<td>Basic understanding except for one new concept</td>
<td>Can draw complete mechanism and explain what the arrows represent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Understands the stereochemistry of the reaction and the impact of the flat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>carbocation but cannot not explain why product is not exactly 50/50 racemic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mixture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can predict between competing mechanisms of $\text{Sn1}$ or $\text{Sn2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>when given only 1 variable</td>
</tr>
<tr>
<td>IV</td>
<td>Full Integration of current topic</td>
<td>Predict between $\text{Sn1}$ or $\text{Sn2}$ mechanisms with multiple</td>
</tr>
<tr>
<td></td>
<td></td>
<td>variables and explain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Predict when rearrangement can occur and draw the rearranged product</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Understands and can explain stereochemistry of the planar intermediate such</td>
</tr>
<tr>
<td></td>
<td></td>
<td>as solvent effects, relationship of rate and concentration of reagent,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can explain the relationship of rate to electrophile’s structure and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nucleophilic strength</td>
</tr>
</tbody>
</table>
Construct for Electrophilic Addition First Activity (Instructor’s Activity 12B) – Bromination, Halohydrin Formation, Epoxidation and Ring Opening

Concepts: Reaction mechanism for electrophilic addition reactions, product stereochemistry, regiochemistry

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Description</th>
<th>Constructs</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Expected Prior Knowledge</td>
<td>Understands alkene electrophilic addition reactions and mechanisms for H₂, HX, H₂O, and X₂</td>
</tr>
<tr>
<td>II</td>
<td>Common Misconception that gives wrong answer</td>
<td>Can predict products of the reactions, but cannot draw complete mechanisms. Regiochemistry or stereochemistry of products may be incorrectly predicted due to an incomplete understanding of the mechanism</td>
</tr>
<tr>
<td>III</td>
<td>Basic understanding except for one new concept</td>
<td>Correctly predicts stereochemistry and region chem. but cannot explain why. Can draw a reasonable mechanism but cannot explain what is happening. Can correctly identify the most electrophilic atoms in each reaction</td>
</tr>
<tr>
<td>IV</td>
<td>Full Integration of current topic</td>
<td>Can explain reasons for stereo or regiospecific reactions. Understands the effect of concentration of multiple nucleophiles in halohydrin formation</td>
</tr>
</tbody>
</table>
Construct for Electrophilic Addition Second Activity (Instructor’s Activity 12C) - Electrophilic Addition to Alkynes

Concepts: Differences in electrophilic addition to alkynes from alkenes, tautomerization, enols and keto forms

<table>
<thead>
<tr>
<th>Developmental Stage</th>
<th>Description</th>
<th>Constructs</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Expected Prior Knowledge</td>
<td>All constructs for Activity 12B</td>
</tr>
<tr>
<td>II</td>
<td>Common Misconception that gives wrong answer</td>
<td>Predicts hydrogenation, bromination, and addition of HX products but is not able to propose a mechanism with incorrect regiochemistry or stereochemistry. May not understand how enol formation affects the addition of water.</td>
</tr>
<tr>
<td>III</td>
<td>Basic understanding except for one new concept</td>
<td>Correctly identifies the electrophile and nucleophile. Predicts correct regio and stereo chem. products. Understands and can draw mechanisms for addition of HX and H₂.</td>
</tr>
<tr>
<td>IV</td>
<td>Full Integration of current topic</td>
<td>Understands and can draw the mechanism for tautomerization. Understands that tautomerization is an equilibrium process accompanied by resonance. Understands and can explain the mechanism and synthesis of vicinal and germinal dihalides. Can predict starting materials and reagents when given products.</td>
</tr>
</tbody>
</table>
APPENDIX D

CLASSROOM ACTIVITY WORKSHEETS
Class Activity 3A

Acids and Bases
Part A: Acids/Bases and pKa values

Model 1: Acid-Base Definitions

<table>
<thead>
<tr>
<th></th>
<th>Arrhenius</th>
<th>Brønsted-Lowry</th>
<th>Lewis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid</td>
<td>Gives $H_2O^+$ in water</td>
<td>Donates $H^+$</td>
<td>Accepts electron pair</td>
</tr>
<tr>
<td>Base</td>
<td>Gives $HO^-$ in water</td>
<td>Accepts $H^+$</td>
<td>Donates electron pair</td>
</tr>
</tbody>
</table>

Questions:
1. (a). In the Brønsted-Lowry definition, what is the role of an acid?
   (b). Which reagent in the reaction shown in Model 1, acts as an acid, HA or $H_2O$?

2. (a). In the Brønsted -Lowry definition, what is the role of a base?
   (b). Which reagent in the reaction shown in Model 1, acts as a base, HA or $H_2O$?

3. (a). In the Lewis definition, what is the role of an acid?
   (b). Which reagent in the reaction shown in Model 1, acts as a Lewis acid, HA or $H_2O$?

4. (a). In the Lewis definition, what is the role of a base?
   (b). Which reagent in the reaction shown in Model 1, acts as a Lewis base, HA or $H_2O$?

5. In the equation shown in Model 1, label the acid, base, conjugate acid and conjugate base.
6. (a). Which definition, Brønsted -Lowry or Lewis, best describes what occurs during the reaction shown below? Explain why one definition is favored.

(b). Label each reactant as acid and base.
Model 2: Acid Dissociation Constant, $K_a$ and $pK_a$

The equilibrium constant ($K_{eq}$) is equal to the concentration of the products over the concentration of the reactants. Since the concentration of water is constant in an acid-base reaction, the acid dissociation constant, $K_a$, is just $K_{eq}$ without the water:

$$K_a = \frac{[H_3O^+][A^-]}{[HA]}$$

and

$$pK_a = -\log K_a$$

Questions:

4. (a). If $K_a$ is large, would the concentration of products or the concentration of the reactants be larger? If $K_a$ is large, the acid is *(circle one)* strong / weak.

(b). If $K_a$ is large, the $pK_a$ is *(circle one)* small / large.

(c). If $K_a$ is small, the $pK_a$ is *(circle one)* small / large.

(d). A small $pK_a$ value means the acid is *(circle one)* strong / weak and a large $pK_a$ means the acid is *(circle one)* strong / weak.

(e). A large $pK_a$ value means the base is *(circle one)* strong / weak.

5. Of the following $pK_a$ values, circle the one that corresponds to the strongest acid.

-10, 1, 5, 30

6. Of the following $pK_a$ values, circle the one that corresponds to the strongest base.

-10, 1, 5, 30

Model 3: $pK_a$ values of Common Acid/Base Pairs

<table>
<thead>
<tr>
<th>Acid (HA)</th>
<th>$pK_a$</th>
<th>Conjugate Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBr</td>
<td>-9</td>
<td>Br$^-$</td>
</tr>
<tr>
<td>HCl</td>
<td>-2.2</td>
<td>Cl$^-$</td>
</tr>
<tr>
<td>CH$_3$CO$_2$H</td>
<td>4.74</td>
<td>CH$_3$CO$_2$-</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>15.7</td>
<td>HO$^-$</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>33</td>
<td>NH$_2^-$</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>~50</td>
<td>CH$_3^-$</td>
</tr>
</tbody>
</table>

Questions:

Refer to the Lewis acid/base definition for the following questions.

7. (a). Of the acids listed in Model 3 which would be least likely to accept an electron pair?

(b). Which would be most likely to accept an electron pair? Explain.

(c). The acid that is the most likely to accept an electron pair is the *(circle one)* stronger / weaker acid.

8. Write out the reaction of HBr with water. First identify the acid and the base, then draw all products formed. Identify the conjugate acid and conjugate base produced.
9. A reaction always proceeds to form the weaker acid (WA) and weaker base (WB) from the stronger acid (SA) and stronger base (SB), i.e. \((SA + SB \rightarrow WA + WB)\). In the following:

\[
\begin{align*}
\text{H}_3\text{C} & \quad \text{pK}_a = 4.7 \\
\text{O} & \\
\text{OH} & \quad \text{pK}_a = 15.7
\end{align*}
\]

(a). Label which reagent will act as the acid and which will act as the base.
(b). Describe what happens to the electron pair that the base donates.

(c). Describe what happens to the electron pair that the acid accepts.

(d). Draw the two products formed in the reaction above. Identify which product is the conjugate acid and which is the conjugate base.

(e). Does the net charge of the reactants equal the net charge of the products drawn? If not recheck your answer.

(f). Predict whether the equilibrium favors the forward or the reverse direction (Hint: compare the pKa values of the reactants to products to determine the stronger acid/base).

10. Weak acids (pKa>6) can act as either acids or bases depending on the environment they are in. In the following reactions:

\[
\begin{align*}
eq 1 & \quad \text{CH}_3\text{OH} + \text{HO}^- & \quad \text{CH}_3\text{O}^- + \text{H}_2\text{O} \\
eq 2 & \quad \text{CH}_3\text{OH} + \text{HBr} & \quad \text{CH}_3\text{OH}_2^- + \text{Br}^-
\end{align*}
\]

(a). Does methanol (CH₃OH) act as the acid or the base in eq. 1? Explain.

(b). Does methanol (CH₃OH) act as the acid or the base in eq. 2? Explain.

(c). Label the acid, base, conjugate acid and conjugate base produced for each reaction.

(d). Once your group has reached consensus on the above questions, discuss and predict an approximate pKa value for methanol, based on values listed in Model 3.
Model 4: Curved Arrows

\[ \text{Eq 3} \]

\[ \text{Eq 4} \]

\[ \text{Eq 5} \]

Questions:
11. (a). Describe what the curved arrow shows when converting the resonance structure on the left to the resonance structure on the right in Eq. 3.

(b). Describe what the curved arrow shows in the reaction shown in Eq. 4.

(c). Describe what is different between the curved arrows in Eq. 3 and those in Eq. 4. Describe what is the same.

(d). Describe what the curved arrow shows in the reaction shown in Eq. 5.

(e). Curved arrows show movement of (circle one)
- protons
- electrons
- atoms

12. Once your group has reached consensus on the above questions, come up with a description of how to draw curved arrows (ie where to start the arrow and where to end it).

13. Draw curved arrows to show formation of the products in reactions 9 and 10 above.

14. Use of curved arrows is an important tool in showing how organic reactions proceed. Based on your description of curved arrows (from #12), explain why the Lewis acid/base definition makes more sense.

15. In the reaction of HBr and H₂O that you wrote in 8 above:
(a). Label the acid and the base (think in terms of the Lewis acid/base definition).
(b). Draw in all lone pairs, then use curved arrows to show the transfer of electrons.
(c). Draw all products formed.
Reflection: on a separate sheet of paper.
As a group, write grammatically correct English sentences to describe three concepts your group has learned from this activity and the one most important unanswered question about this activity that remains with your group. Place this in your group folder before leaving class.

Additional Questions

16. Identify the acid and the base in each of the following acid base reactions, then draw all the products expected. Use curved arrows to show how the product was formed. Predict if the reaction will go in the forward or the reverse direction.

(a).

(b).

(c).

(d).

aspirin

(e).

(f).

More information about Acids and Bases can be found in your textbook in Chapter 1, pages 21-30. Additional problems on acids and bases include those problems within the above sections, and the following problems found at the end of Chapter 1: 42-46.
Class Activity 3B
Acids and Bases
Part B: Predicting Acid/Base Strength Without pKa Values

Model 1: Stability of Conjugate Base
The strength of an acid can be predicted by estimating the stability of the conjugate base formed. The stability of a base is affected by the following factors: formal charge, electronegativity, inductive electron withdrawing effect, size, resonance stabilization and hybridization.

Questions:
1. (a). Consider the reverse direction of the above reaction, if the base A⁻ is stable, is it (circle one) more likely / less likely to donate an electron pair (to form HA)?

(b). In the reverse direction of the above reaction, if the base A⁻ is unstable, is it (circle one) more likely / less likely to donate an electron pair (to form HA)?

(c). Is an unstable base more reactive or less reactive?

2. (a). In the forward direction of the above reaction (Model 1), if the conjugate base is stable, would the acid be (circle one) more likely / less likely to accept an electron pair?

(b). In the forward direction of the above reaction (Model 1), if the conjugate base is unstable, would the acid be (circle one) more likely / less likely to accept an electron pair?

(c). The more stable the conjugate base, then the acid it is derived from is (circle one) stronger / weaker.

3. (a). Calculate the formal charge of oxygen in each of the following molecules. Which of the two compounds would you expect to be more stable and why?

(b). Calculate the formal charge of carbon in each of the following molecules. Which compound would you expect to be more stable and why?

(c). Once your group has reached consensus on the above questions, write a grammatically correct sentence about how formal charge affects the stability and the strength of a base.
Model 2: Acid/Base Strength and Electronegativity Values

<table>
<thead>
<tr>
<th>Element</th>
<th>Electronegativity</th>
<th>pKa</th>
<th>HA → H⁺ + A⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>4.0</td>
<td>3.2</td>
<td>HF → H⁺ + F⁻</td>
</tr>
<tr>
<td>O</td>
<td>3.4</td>
<td>15.7</td>
<td>H₂O → H⁺ + HO⁻</td>
</tr>
<tr>
<td>N</td>
<td>3.0</td>
<td>36</td>
<td>NH₃ → H⁺ + NH₂⁻</td>
</tr>
<tr>
<td>C</td>
<td>2.5</td>
<td>40</td>
<td>HCH₃ → H⁺ + H₂C⁻</td>
</tr>
</tbody>
</table>

Compare electronegativity of elements of similar size.

Questions
5. (a). Of the four elements listed in Model 2, which element is the most electronegative? Which element is the least electronegative?

(b). An electronegative element (circle one) attracts / repels electrons.

(c). In the general reaction HA → H⁺ + A⁻, which conjugate base (A⁻) would be more stable, the one derived from the more electronegative element or the least electronegative element as noted in 5a above? Explain.

(d). Of the four conjugate bases listed in Model 2, (F⁻, HO⁻, H₂N⁻, H₂C⁻) rank them from most stable to least stable. What conclusions can you make about how electronegativity affects the stability and the strength of the conjugate base?

(e). Once your group has reached agreement, construct a statement on how the stability of the conjugate base relates to the pKa values listed in Model 2.

Model 3: Acid/Base Strength and Inductive Electron Withdrawing Effects

\[ \text{C} \quad \text{F} \]

Questions:
6. (a). Which atom in the above model is more electronegative, C or F?

(b). Would the electrons in the covalent C-F bond be equally shared or not? Explain.

(c). If the electrons are not equally shared, which atom (C or F) would the electrons be attracted to?

(d). Indicate which atom would have a partial negative charge and which atom would have a partial positive charge (label with δ⁻ and δ⁺) in the C-F bond.
7. A difference in electronegativity between atoms causes what is called the inductive electron withdrawing effect, which is shown by a dipole arrow. Draw a dipole arrow over any bonds of those shown below that are considered to be polar.

\[
\begin{array}{cccccc}
\text{C} & - & \text{C} & \text{C} & \text{O} & \text{Br} & \text{C} & \text{H} & \text{Cl} & \text{N} & \text{C}
\end{array}
\]

8. (a). Draw dipole arrows for each of the polar bonds in the following bases (Hint: the C—H bond is considered to be non-polar).

\[
\begin{array}{cc}
\Theta & :& \text{C} & \text{H} \\
\text{H} & & \text{F} \\
\Theta & :& \text{C} & \text{F} \\
\text{H} & & \text{F}
\end{array}
\]

(b). For each base, compare the atom with the negative charge. Determine if there are any differences in electronegativity of that atom, size or charge. Explain.

(c). For each base, compare the bonds to the atom with the negative charge. Are there any differences in polarity of these bonds? Explain.

(d). What effect would a polar bond like C—F have on the negative charge of the carbon?

(e). Which base would be the most stable? Explain why.

---

Model 4: Acid/Base Strength and Size

<table>
<thead>
<tr>
<th>Element</th>
<th>pKa</th>
<th>HA → H⁺ + A⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>3.2</td>
<td>HF → H⁺ + F⁻</td>
</tr>
<tr>
<td>Cl</td>
<td>-2.2</td>
<td>HCl → H⁺ + Cl⁻</td>
</tr>
<tr>
<td>Br</td>
<td>-9</td>
<td>HBr → H⁺ + Br⁻</td>
</tr>
<tr>
<td>I</td>
<td>-10</td>
<td>HI → H⁺ + I⁻</td>
</tr>
</tbody>
</table>

Questions:
9. From the information shown in Model 4:
   (a). Which element is the largest in size? Which element is the smallest?
   (b). How does the size of the element relate to the pKa values given?
   (c). What conclusions can you make about how size affects the stability of the base? (Hint: use the term “polarizability” in your answer).
10. Use the scheme below showing the acid dissociation of acetic acid and of methanol to answer the following questions.

\[
\begin{align*}
\text{acetic acid} & \quad \overset{\text{+H} \ominus}{=} & \quad \text{H}_2\text{C} = \text{O} \\
\text{methanol} & \quad \overset{\text{+H} \ominus}{=} & \quad \text{H}_2\text{CO} \ominus \\
\end{align*}
\]

(a). Identify the conjugate base for each of the above reactions.

(b). Compare the conjugate base from each reaction. Focus on the atom that contains the charge and determine if there are any differences in electronegativity, charge or size.

(c). Draw all possible resonance structures for each conjugate base shown above.

(d). Resonance forms show that electrons can be spread out or delocalized, which has a stabilizing effect. What conclusions can you make about how resonance stabilization affects stability of the conjugate base?

(e). Based on your answer for (d) above, which would be the more acidic, acetic acid or methanol? Explain.

---

Model 5: Acid/Base Strength and Hybridization

\[
\begin{align*}
\text{H}_2\text{C} = \text{CH}_3 & \quad + \quad \text{B} \ominus & \quad \overset{\text{+H} \ominus}{=} & \quad \text{H}_2\text{C} = \text{CH}_2 \ominus & \quad + \quad \text{HB} & \quad \text{pK}_a=50 & \quad \text{Eq. 6} \\
\text{H}_2\text{C} = \text{CH}_2 & \quad + \quad \text{B} \ominus & \quad \overset{\text{+H} \ominus}{=} & \quad \text{H}_2\text{C} = \text{CH} \ominus & \quad + \quad \text{HB} & \quad \text{pK}_a=44 & \quad \text{Eq. 7} \\
\text{HC} = \text{CH} & \quad + \quad \text{B} \ominus & \quad \overset{\text{+H} \ominus}{=} & \quad \text{HC} = \text{C} \ominus & \quad + \quad \text{HB} & \quad \text{pK}_a=25 & \quad \text{Eq. 8} \\
\end{align*}
\]

Questions:

11. (a). Using the pK\text{a} values, which compound is most acidic, that from Eq. 6, 7 or 8?

(b). Compare the conjugate base from each reaction. Focus on the atom that contains the charge and determine if there are any differences in electronegativity, charge size or resonance.
(c). What is the hybridization of each carbon in each of the starting materials in Eq. 6, 7, 8?

(d). Are there any differences in hybridization between the conjugate bases in Eq. 6, 7, 8?

(e). Based on hybridization, which compound has the most s-character? Which has the least s-character? How does the amount of s-character relate to acidity?

(f). Once your group has reached agreement, construct a statement on how the s-character (or hybridization) of the conjugate base relates to the pKa values.

Reflection: on a separate sheet of paper.
As a group, write grammatically correct English sentences to describe three concepts your group has learned from this activity and the one most important unanswered question about this activity that remains with your group. Place this in your group folder before leaving class.

Additional questions:

12. Use the structures shown in the scheme below to answer the following questions.

![Structures](image)

(a). Draw the acid-base reaction of CF₃CO₂H acting as an acid.

(b). Draw the acid-base reaction of acetic acid (CH₃CO₂H) acting as an acid.

(c). Which conjugate base from part (a) or part (b) would be the most stable? Explain.

(d). How does the stability of the conjugate bases relate to the acidity of the acids (i.e. which acid would be the stronger acid)? Explain.

13. For each compound, circle the most acidic H.
(a). Explain how compound I demonstrates that the electronegativity effect is stronger than the inductive effect.

(b). Explain how compound II demonstrates that the formal charge effect is stronger than the electronegativity effect.

(c). Explain how the inductive effect makes the acidity of the two HO groups in compound III different.

14. Rank the following compounds from most acidic to least acidic.
   (a). CH₃CH₂OH, CH₃CH₂OH, CH₃CH₂NH₂
   (b). CH₃CH₂CH₂, CH₃CH₂OH, CH₃CH₂CO₂H
   (c). BrCH₂CO₂H, CH₃CH₂CO₂H, CH₃CH₂CH₂OH
   (d). CH₃CH₂NH₂, (CH₃)₃N, CH₃CH₂OH

15. Rank the following compounds from most basic to least basic.
   (a). CH₃CH₂⁻, CH₃O⁻, CH₃NH⁻
   (b). CH₃⁺, HO⁻, Br⁻
   (c). CH₃CO₂⁻, CH₃CH₂O⁻, BrCH₂CO₂⁻

More information about Acids and Bases can be found in your textbook in Chapter 1, pages 21-30. Additional problems on acids and bases include those problems within the above sections, and the following problems found at the end of Chapter 1: 42-46.
Class Activity 9A

Substitution Nucleophilic Bimolecular, SN2
One-step nucleophilic substitution.

Model 1: Nucleophilic Substitution Reactions
In a substitution reaction, an incoming group replaces another group referred to as the leaving group. Two examples of substitution reactions are shown below.

Questions
1. For each reaction in Model 1:
   (a) Identify the incoming group (on the reactants side) by drawing a box around it.
   (b) Circle the leaving group (on the reactants side).
   (c) Can incoming groups and leaving groups contain more than one atom?
   (d) Provide an explanation for why these reactions are called substitution reactions.

2. Add a δ+ and δ- on the compounds that contain the leaving group to indicate which way the C-leaving group bond is polarized.

3. Use curved arrows to illustrate the mechanism that will accomplish each substitution reaction shown in Model 1. (Remember that curved arrows show electron movement.)

4. For the following questions remember that “chile” means “lover of”:
   (a) What is the charge of a nucleus, (circle one) + or -?
   (b) A nucleophile is attracted to another atom with what charge, (circle one) + or –?
   (c) A nucleophile has electrons to (circle one) donate / accept. Based on this answer, would a nucleophile be considered a Lewis Acid or a Lewis Base?
   (d) For the two reactions in Model 1, identify the nucleophile in each reaction.
   (e) An electrophile is an atom that is attracted to another atom with (circle one) + or – charge?
   (f) An electrophile has electrons to (circle one) donate / accept. Based on this answer, would an electrophile be considered a Lewis Acid or a Lewis Base?
   (g) For the two reactions in Model 1, identify the atom that is acting as the electrophile.
Model 2: One-Step Nucleophilic Substitution (SN2)
The mechanism for an SN2 reaction is shown below. The transition state is the highest potential energy species between the reactant and the product.

Questions
5. For the reaction shown in Model 2:
   (a). How many reactants are involved in the reaction?
   (b). Label the nucleophile (Nu-) and electrophile (E+), and circle the leaving group.
   (c). What bond is being formed in this reaction? ______. What bond is being broken? ______.
   (d). Draw curved arrows to show electron movement.

6. Focus on the transition state for the reaction shown in Model 2:
   (a). How many of the reactants are present in the transition state?
   (b). Based on your answer for 6a, explain why the SN2 reaction is bimolecular.

   (c). The rate equation for the SN2 reaction is Rate = [CH3Br][I']. Explain how the rate equation supports a bimolecular transition state.

   (d). The dotted line in the transition state represents a partial bond. Does this suggest that the bonds are being formed and broken at the same time or stepwise? Explain your answer.

   (e). Based on your answer for 6c, explain why the SN2 reaction is a concerted reaction. (concerted means performed in unison).

   (f). In the transition state is the incoming group (Nu-) on the same or the opposite side of the leaving group? Draw an alternate transition state where the incoming group and the leaving group are different from what is shown. Once your group agrees on an alternate transition state, determine if this transition state is more or less favorable than the one in Model 2.

7. Draw a potential energy diagram to illustrate the reaction mechanism shown in Model 2. Label with reactants, transition state and product structures.
8. Focus on the stereochemistry of the following reaction:

\[ \text{CH}_3\text{CH}_2\text{I} \rightleftharpoons h^+ \text{CH}_3\text{CH}_2\text{Br} \rightarrow \text{CH}_3\text{CH}_2\text{Br} \]

(a) What does the stereochemistry tell you about the approach of the nucleophile with reference to the leaving group?

(b) Explain how the product above proves which transition state is correct (hint: use R and S in explaining your answer).

---

Model 3: Nucleophiles
A nucleophile (Nu) is defined as a “nucleus lover” or a species which donates electrons. (refer to question 4 above).

| HO⁻ | CH₃OH | H₂ | H₃C⁺ | H₃N⁺ |

Questions
9. For the compounds listed in Model 3:
   (a) Circle the compounds that could act as nucleophiles, cross out those that would not.
   (b) Explain why the compounds circled could act as nucleophiles

(c). What one feature must all nucleophiles have?

(d). Explain why the crossed out compounds would not act as nucleophiles.

10. Determine which compound in each of the following pairs is the better nucleophile. Explain your answer using terms such as charge, electronegativity, size, basicity and polarizability.

(a).

CH₃O⁻ vs CH₃OH

(b).

CH₃⁻ vs NH₂⁻

(c).

HO⁻ vs F⁻

(d).

I⁻ vs Cl⁻

(e).

\[ \text{O} \]
Model 4: Electrophiles
An electrophile (E+) is defined as a "electron lover" or a species which accepts electrons. (refer to question 4 above).

\[
\begin{array}{|c|c|c|}
\hline
\text{HO} & \text{CH}_3\text{Br} & \text{(CH}_3\text{)_2CH}^+ \text{CH}_3\text{NH}_2 \\
\hline
\end{array}
\]

Questions
11. For the compounds listed in Model 4:
   (a). Circle the compounds that could act as electrophiles, cross out those that would not.
   (b). Explain why the compounds circled could act as electrophiles
   (c). What one feature must all electrophiles have?
   (d). Explain why the crossed out compounds would not act as electrophiles.

12. Consider the following reaction:
   \[
   \text{R-X} \quad \text{\textless<=>\textgreater} \quad \text{R}^+ + \text{X}^-
   \]
   (a). Label the R\text{X} bond with \delta^+ and \delta^- to indicate bond polarity.
   (b). Why would R\text{X} be considered to be a good electrophile?

13. Consider the acid dissociation of H\text{X} below:
   \[
   \text{H-X} \quad \text{\textless<=>\textgreater} \quad \text{H}^+ + \text{X}^-
   \]
   (a). If X\text{^\circ} is stable, is H\text{X} likely to accept an electron pair (to form products)? Explain.
   (b). If X\text{^\circ} is a strong base, is H\text{X} likely to accept an electron pair (to form products)? Explain.
   (c). If X\text{^\circ} is a weak base, is H\text{X} likely to accept an electron pair (to form products)? Explain.

14. Determine which compound in each of the following pairs is the better leaving group. Explain your answer using terms such as charge, electronegativity, size, basicity and polarizability.
   (a).
   \[
   \text{I}^- \quad \text{vs} \quad \text{Cl}^- \\
   \]
   (b).
   \[
   \text{Br}^- \quad \text{vs} \quad \text{F}^- \\
   \]
   (c).
   \[
   \text{HO}^- \quad \text{vs} \quad \text{Cl}^- \\
   \]
   (d).
   \[
   \text{HO}^- \quad \text{vs} \quad \text{H}_2\text{O} \\
   \]
Model 5: Lewis Acid/Base Revisited

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Acceptor</th>
<th>Donor</th>
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</tr>
</thead>
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<tr>
<td>HI</td>
<td>H⁺</td>
<td>I⁻</td>
<td>-10</td>
</tr>
<tr>
<td>CH₃OH</td>
<td>H⁺</td>
<td>CH₃O⁻</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Questions:
15. (a). A Lewis Base (circle one) donates / accepts an electron pair.
(b). A nucleophile (circle one) donates / accepts an electron pair.
(c). A Lewis Acid (circle one) donates / accepts an electron pair.
(d). An electrophile (circle one) donates / accepts an electron pair.
(e). Identify the Lewis acid and Lewis base in each of the above reactions.

16. (a). From the pKa values listed in Model 5, determine which is the stronger acid, HI or CH₃OH. Explain your choice.
(b). Compare the conjugate base produced in each reaction. Explain why the conjugate base produced from the predicted stronger acid is a weaker base (more stable) than the conjugate base produced in the other reaction. (use terms like charge, induction, electronegativity, size to explain your answer).
(c). Use the pKa values listed in Model 5 to determine which direction the following reaction will proceed. Explain your answer based on the strength/stability of the Lewis Base.

\[
\text{CH}_3\text{CH}_2\text{I} + \text{CH}_3\text{OCH}_3 \rightarrow \text{CH}_3\text{CH}_2\text{OCH}_3 + \text{I}^-
\]

Reflection: on a separate sheet of paper.
As a group, write grammatically correct English sentences to describe three concepts your group has learned from this activity and the one most important unanswered question about this activity that remains with your group. Place this in your group folder before leaving class.

Additional Questions
17. Steric hindrance is the unfavorable electron-electron repulsion that results when bonds are forced too close to each other.
(a). Draw the SN2 mechanism using curved arrows for the reaction of bromoethane with Nu⁻.

(b). Draw the SN2 mechanism using curved arrows for the reaction of 2-bromopropane with Nu⁻.
(c). Given that steric hindrance is unfavorable, predict whether the SN2 reaction of bromoethane or 2 bromopropane would be faster.

(d). Determine in general the order of reactivity of all alkyl halides in an SN2 reaction (methyl, 1° etc.)

18. Predict the product of each of the following reactions, showing stereochemistry if appropriate. Identify the nucleophile and electrophile.

(a).

(b).

More information about one-step substitution (SN2) reactions can be found in Chapter 6 of your textbook, sections 6.8 - 6.12. Additional problems on SN2 reactions include those problems within the above sections, and the following problems found at the end of Chapter 6: 44, 46, 48, 56.
Class Activity 9B

Substitution Nucleophilic Unimolecular, SN1
Two-step nucleophilic substitution.

Model 1: Two-Step Nucleophilic Substitution (SN1)
In a two step substitution reaction (SN1) mechanism, the first step is slow and is the rate determining step, while the second step is fast.

Questions
1. For the reaction shown in Model 1 above:
   (a). What bonds are formed/broken in the first step of the SN1 reaction?
   (b). What bonds are formed/broken in the second step of the SN1 reaction?
   (c). Label the nucleophile (Nu-) and the electrophile (E+) and circle the leaving group.
   (d). Draw curved arrows to show electron movement.
   (e). Step 3 in Model 1 (deprotonation) involves loss of the proton that was part of the incoming group, to return the oxygen to a neutral charge. Draw curved arrows to illustrate this proton loss.

2. The mechanism for an SN1 reaction occurs in two steps as shown in Model 1:
   (a). Why do you expect the first step to be slow and the second step to be fast?
   (b). Which step would be the rate determining step?
   (c). How many reactants are involved in the rate determining step?
   (d). Based on your answer to 2c above, explain why the SN1 reaction is unimolecular.
   (e). The rate equation for an SN1 reaction is Rate = k[CH3Br]. Explain how the rate equation supports a unimolecular reaction.

3. Focus on the carbocation intermediate formed in the SN1 mechanism.
   (a). What is the hybridization of the carbon with the \( \oplus \) charge?
   (b). What is the shape of the carbocation structure (tetrahedral, trigonal planar etc.)?
   (c). How many valence electrons does the carbon with the \( \oplus \) charge have?
   (d). Is the carbocation electron rich or electron deficient?
(e). Which will the carbocation most likely react with, electron rich or electron deficient reagents? Based on this answer, would the carbocation be a Lewis Acid or a Lewis Base?

(f). Rank the following carbocations from most stable (1) to least stable (4).

<table>
<thead>
<tr>
<th>H₂C</th>
<th>H₂C</th>
<th>H₂C</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>CH₃CH₂</td>
<td>CH₃CH₂</td>
<td>CH₃CH₂</td>
</tr>
</tbody>
</table>

4. A potential energy diagram that illustrates the first step of the SN1 reaction is shown below.

(a). Label each R⁺ intermediate as 1°, 2° or 3°, based on relative stability predicted above.
(b). Which cation will be of the lowest energy (compare to 3° above)?
(c). Determine the general order of reactivity of alkyl halides in an SN1 reaction (methyl, 1° etc.)

(d). Draw a potential energy diagram that illustrates the entire two-step SN1 reaction mechanism that shows conversion of RX → R⁺ → RNu.

5. (a). Draw the carbocation that would form after the first step of an SN1 mechanism for the following compound:

(b). Draw the product obtained if a nucleophile (CH₃OH) attacks the carbocation from the TOP of the carbocation. Determine whether this is the R or the S isomer.
(c). Draw the product obtained if a nucleophile (CH₃OH) attacks the carbocation from the BOTTOM of the carbocation. Determine whether this is the R or the S isomer.
(d). What is the relationship between the products formed in (b) and (c) above?
(e). Retention of configuration means that the incoming group replaced the leaving group on the same side. Which product (b) or (c) shows retention of configuration?

(f). Inversion of configuration means that the incoming group replaced the leaving group on the opposite side. Which product (b) or (c) shows inversion of configuration?

(g). Once your group has reached agreement on the above questions, determine if the products from (b) and (c) above would be formed in equal amounts or not? If not in equal amounts, which product would be favored? Explain your answer.

**Model 2: Rearrangements**

Any time a carbocation intermediate is formed rearrangements are possible.

![Diagram of rearrangements]

**Questions**

6. For the rearrangement (step 1) of the reaction in Model 2:

   (a). Label the cations A and B as 1°, 2° or 3°. Which cation is more stable?

   (b). In the rearrangement of cation A to cation B, what bonds are being formed/broken?

   (c). Explain what the curved arrow represents in showing the rearrangement.

   (d). Hydride ion is represented as [H:Θ]. Explain why this rearrangement is called a hydride shift and NOT a proton shift?

   (e). Once your group has reached consensus on the above questions, determine why the rearrangement from cation A to B is fast. Would the reverse (B to A) be favored as well? Explain.

7. Draw the carbocations formed from migration of Ha, and from migration of Hb.

![Diagram of migration]

   (b). Identify all the carbocations (the initial cation as well as the cations formed on rearrangement of Ha and Hb) as 1°, 2°, or 3°.

   (c). Based on the stability of the carbocations which proton, Ha or Hb, will be more likely to migrate?
Model 3: SN1 vs SN2 Mechanism

Questions
8. For the reaction labeled SN2 in Model 3:
   (a). Identify the type of alkyl halide (1°, 2°, 3°). What alkyl halide reacts fastest in an SN2 reaction? Explain why.

   (b). Identify the nucleophile as strong or weak.
   (c). For SN2 reactions, Rate=k[RX][Nu]. Is the concentration or strength of the nucleophile important in an SN2 reaction? Explain.

   (d). Identify the solvent as polar protic or aprotic. Would this solvent be capable of hydrogen bonding with the nucleophile? How would this affect the strength of the nucleophile?

9. For the reaction labeled SN1 in Model 5:
   (a). Identify the type of alkyl halide (1°, 2°, 3°). What alkyl halide reacts fastest in an SN1 reaction? Explain why.

   (b). Identify the nucleophile as strong or weak.
   (c). For SN1 reactions, Rate=k[RX]. Is the concentration or strength of the nucleophile important in an SN1 reaction? Explain.

   (d). Identify the solvent as polar protic or aprotic. Would this solvent be capable of hydrogen bonding with the leaving group? Would the solvent be capable of stabilizing the cationic intermediate through dipole interactions? How would these factors affect the stability of the intermediate?

10. Once your group has reached consensus on the above questions, come up with a list of factors used to predict whether SN1 or SN2 will occur.

Reflection: on a separate sheet of paper.
As a group, write grammatically correct English sentences to describe three concepts your group has learned from this activity and the one most important unanswered question about this activity that remains with your group. Place this in your group folder before leaving class.
Additional Questions

11. Secondary alkyl halides can undergo substitution either by the SN1 or SN2 mechanism. The reaction conditions determine which pathway is followed. Explain each of the following:

   SN2 is favored when the concentration of nucleophile is high.

   SN1 is favored when the concentration of nucleophile is low.

   SN2 is favored when there is a strong nucleophile.

   SN1 is favored when there is a weak nucleophile (H₂O, ROH).

   SN2 is favored in a polar aprotic solvent.

   SN1 is favored in a polar protic solvent.

12. Rationalize the formation of the following product (show mechanism).

\[
\begin{align*}
\text{Br} & \quad \xrightarrow{\text{H₂O}} \quad \text{OH} \\
\end{align*}
\]

More information about two-step substitution (SN1) reactions can be found in Chapter 6 of your textbook, sections 6.13 – 6.16. Additional problems on SN1 reactions include those problems within the above sections, and the following problems found at the end of Chapter 6: 41, 51, 54, 67.
Class Activity 12B

Electrophilic Addition

Part B: Additions Involving Cyclic Intermediates or Products

Model 1: Halogenation of Alkenes

The addition of bromine or chlorine to an alkene is called halogenation. The first step of this reaction forms a cyclic intermediate which goes on to form a vicinal dibromide product.

Questions:

1. (a). Is an alkene electron rich or electron deficient? Would the alkene act as a nucleophile or an electrophile in an addition reaction?
   (b). Consider the Br-Br bond. If an electron rich species were to approach one end of this bond (for here assume the electron rich species approaches the left side), what affect would this have on the dipole of the Br-Br bond? Draw δ+ and δ- signs on the bromine in Model 1 to illustrate this induced dipole. Label the atom that would act as the electrophile.

2. (a). In step 1 identify what bonds are being formed and broken.
   (b). Draw curved arrows for step 1 to illustrate electron movement. Where must the electrons come from to form the second C-Br bond?
   (c). The cyclic bromonium ion has a positive charge on Br. How many lone pair electrons are present on the Br? Draw the lone pair electrons in on the above model.
   (d). In forming the second C-Br bond, the cyclic bromonium ion results. If this bond did not form, the following cation would have resulted. Compare the stability of this cation to the cyclic bromonium ion. Which would you expect to be more stable? How does this explain why the cyclic bromonium ion is formed rather than the cation shown?

   (e). From what face of the original cyclopentene did the bromine approach? (look at the stereochemistry of the cyclic bromonium ion). Would you expect the bromine to approach the other face of the alkene (not shown) as well? Explain.

3. (a). For step 2, label the electrophile and the nucleophile.
   (b). Draw curved arrows for step 2 to illustrate electron movement.
   (c). What is the regiochemical relationship between the Br atoms in the product vicinal dibromide?
(d). What is the stereochemical relationship between the Br groups of the vicinal dibromide? Once your group has reached agreement, explain if this result would support SYN or ANTI addition of the halogen.

Model 2: Halohydrin formation

Answers

4. (a). Compare the reactions in Model 2 and Model 1. Are there any differences in the reagents? Are there any differences in the stereochemistry of addition (SYN or ANTI)?

(b). What two functional groups does a vicinal dibromide have? What two functional groups does a halohydrin have? What is the main difference between these two products (from Models 1 & 2)?

(c). Would you expect the first step in Model 2 to be the same as that in Model 1? Explain why.

(d). The cyclic bromonium ion is the intermediate in halohydrin formation. Which reagent, from those listed in Model 2, must be added to the cyclic bromonium ion to give the halohydrin?

(e) Use curved arrows to draw the complete mechanism for halohydrin formation (refer to Model 1 as an example). Make sure everyone in your group is in agreement.

5. The following is an example of halohydrin formation with an unsymmetrical alkene (stereochemistry is omitted for simplicity).

(a). The two possible halohydrin products, A and B, are shown. What is the relationship between these compounds? (conformational, constitutional, stereoisomers etc.)

(b). Draw a curved arrow showing how the water must attack the halohydrin to form product A (label arrow as A). Is this arrow pointing to the more substituted or the less substituted carbon of the intermediate?

(c). Similarly draw a curved arrow showing how the water must attack form product B (label arrow as B). Is this arrow pointing to the more substituted or the less substituted carbon of the intermediate?
(d). Since only product A is formed, this reaction is said to be regioselective. Using your answers to b and c, come up with a rule for where nucleophilic attack occurs on the cyclic bromonium ion.

(e). Once your group has reached consensus on the above questions, discuss why attack is regioselective. (Hint: consider which one of the C-Br bonds of the cyclic bromonium ion would be more likely to break). Is the regioselectivity in this reaction controlled by electronic factors or by steric factors? Is the mechanism $S_n1$-like or $S_n2$-like? Explain.

---

Model 3: Epoxidation of Alkenes

Questions:
6. A peroxyacid has the general formula of $R\text{CO}_2\text{H}$ (the R group can be anything).
   (a). Given that an O-C bond is weak, predict which oxygen of the peroxyacid is likely to act as the electrophile.

   (b). Draw the reaction of the alkene with the electrophilic oxygen using curved arrows to show electron movement (consider for now that the reaction is stepwise and you are just showing the first step). Does the leaving group (after breaking the O-O bond) help explain why one oxygen is more electrophilic? Explain.

   (c). The mechanism for epoxidation is concerted with the transition state shown below. Draw curved arrows on the reactants to illustrate the electron movement in forming the transition state.

   (d). Does the mechanism above support SYN addition? Explain.

7. The geometry of the alkene is maintained in epoxidation reactions. This means that if two groups on the alkene were cis, they would remain cis in the epoxide product.
   (a). In the following scheme, circle the products that clearly show retention of alkene geometry on epoxidation with a peroxyacid.
(b). Draw the products formed on reaction of the following alkene with a peroxyacid, showing syn addition and retention of alkene geometry.

\[
\begin{array}{c}
\text{Ph} \quad \text{CH}_2 \\
\text{H} \quad \text{Ph} \quad \text{RCOOH}
\end{array}
\]

**Model 4: Epoxide Ring Cleavage**

Questions

6. (a). Epoxides are strained three membered rings. Are the C-O bonds of an epoxide considered polar or non-polar? If polar label each C-O bond with δ+ and δ- to indicate the polarity.

(b). Would the carbons of the epoxide be electron deficient or electron rich?

(c). What atom of the epoxide would most likely be attacked in the presence of a nucleophile? Explain why.

(d). Would you expect the nucleophile to attack on the same side or the opposite side of the epoxide? (explain why - compare to attack of cyclic bromonium in question 3f).

9. Use curved arrows to show electron movement in the reaction listed in Model 4.

10. (a). Consider the unsymmetrical epoxide shown below. On reaction with a nucleophile, which carbon would most likely be attacked, the more or less substituted? (Compare to question 5d & 5e). Draw the product expected.

\[
\begin{array}{c}
\text{H}_2\text{C} \\
\text{H}_3\text{C}
\end{array}
\xrightarrow{\text{NaCN}}
\]

(b). Is the regioselectivity in this reaction controlled by electronic factors or by steric factors? Is the mechanism \( S_{N1} \)-like or \( S_{N2} \)-like? Explain.

Reflection: on a separate sheet of paper.
As a group, write grammatically correct English sentences to describe three concepts your group has learned from this activity and the one most important unanswered question about this activity that remains with your group. Place this in your group folder before leaving class.
Additional Questions

11. Reaction of an epoxide with acid in water gives a 1,2-diol as shown below.

(a). Is the 1,2-diol cis or trans?
(b). Does the 1,2-diol formed from reaction of the epoxide have the same stereochemistry as the product formed in question 11?
(c). Using the halogenation of alkenes as a reference, propose a mechanism for this transformation, using curved arrows to show electron movement. (Hint: if a species is positive, it will act as the electrophile, so search for something in the reagents that can donate electrons and act as the nucleophile. Do this for each step until the product is reached).

12. Draw the missing reagents/products in the following reactions.

13. Draw the products of the following reactions (some were covered in class). Show stereochemistry if relevant.
Class Activity 12C

Electrophilic Addition to Alkynes

Model 1: Electrophilic Addition of HX to an Alkyne

Questions:
1. (a). How many \( \pi \)-bonds does an alkyne have?
   (b). Would an alkyne act as a nucleophile or an electrophile? Why?
   (c). Would you expect an alkyne react in a similar fashion to an alkene? Explain.
   (d). In the example in Model 1, how many \( \pi \) bonds reacted after step 1? How many after step 2?

2. Consider the addition of HBr to an alkyne as shown in Model 1:
   (a). Draw the two possible vinyl cations (using curved arrows to show formation) after the addition of H\(^+\) in step 1.
   (b). Of the two vinyl cations drawn above, which would be the most favorable?
   (c). Does this follow Markovnikov's rule? Explain.
   (d). Starting with the vinyl bromide, draw (using curved arrows) the two possible cations formed after the addition of H\(^+\) in step 2.
   (e). Of the two cations drawn in (d) above, which would be the most favorable? Explain why (use resonance forms to help explain your answer).

3. In the addition of HBr to 2-pentyne:
   (a). Draw the two possible cations that could form after the addition of H\(^+\) in the first step.
   (b). Of the two cations drawn in (3a) above would you expect any difference in stability? Explain.
   (c). Draw the geminal dibromides expected on reaction of 2-pentyne with excess HBr. Explain if these products will be formed in equal amounts or not.
4. The addition of halogens to alkynes is similar to the addition to alkenes, except that both syn and anti addition can occur.
   (a). Draw the products expected on addition of 1 equivalent of Br₂ to 2-pentyne. Which geometric isomer would you expect to be the major product?
   (b). Draw the product(s) expected on addition of 2 equivalents of Br₂ to 2-pentyne.

---

Model 2: Hydrogenation of Alkynes (Addition of H₂)
The hydrogenation of an alkyne occurs on addition of hydrogen to the alkyne in the presence of a catalyst.

Questions:
5. When excess hydrogen is added to an alkyne in the presence of palladium catalyst (eq. 1 of Model 2), what is the resulting product?
6. When excess hydrogen is added to an alkyne in the presence of Lindlar's catalyst, (eq 2 of Model 2), what is the resulting product?
7. Lindlar's catalyst is referred to as a "poisoned catalyst". Give an explanation for this term.

8. Hydrogenation of an alkyne occurs to give SYN addition of the hydrogen.
   (a). If SYN addition occurs to give an alkene, would you expect the geometry of the alkene to be cis or trans?
   (b). Draw the product expected on hydrogenation of the following alkyne in the presence of Lindlar's catalyst, clearly showing geometry of the double bond.

(c). Can the alkene drawn above be rotated so that the opposite geometric isomer is formed? If not, how would the mechanism of hydration need to be altered in general terms so that the opposite geometric isomer could be formed?
Model 3: Hydration of Alkynes (Addition of H₂O)
Hydration of an alkyne occurs to give a vinyl alcohol or enol. Vinyl alcohols are not stable and rapidly undergo tautomerization to form an aldehyde or ketone (this is called keto-enol tautomerization). The hydration can be accomplished in the presence of a mercury catalyst (H₂O, HgOAc₂, H₂SO₄) or via hydroboration (R₂BH, H₂O₂, NaOH).

![Chemical reaction diagram]

9. (a) Compare the hydration of propene to that of propyne. First draw the product that would form on reaction of propene with H₂SO₄ and H₂O. Then compare this product with the vinyl alcohol shown above for hydration of propyne. What is different about the two products?

(b) In the hydration of propyne, does addition occur according to Markovnikov's rule? Is this the same as hydration of alkenes?

10. Keto-enol tautomerization is often called a proton jump as the proton on the OH group "jumps" to the neighboring carbon as shown in Model 3.
   (a) What bonds are being broken in the vinyl alcohol when undergoing tautomerization?
   (b) What bonds are being formed in tautomerization to give the ketone?

(c) Draw the keto form of each of the following enols.

11. (a) Devise a mechanism for the following reaction, using curved arrows to show electron movement.

   ![Mechanism diagram]

(b) Is the product shown above the Markovnikov or anti-Markovnikov product?

(c) Draw the enol that would lead to the product drawn below. Is this enol a result of Markovnikov or anti-Markovnikov addition?
(d). Explain why the product shown in (a) is the major product and not the one shown in (c).

(e). What reagents would you have to use to form the product given in (c) above?

Reflection: on a separate sheet of paper.
As a group, write grammatically correct English sentences to describe three concepts your group has learned from this activity and the one most important unanswered question about this activity that remains with your group. Place this in your group folder before leaving class.

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**Additional Questions**

12. Provide reagents that would accomplish each of the following transformations.

(a). \[ R\equiv\equiv H \rightarrow \]

(b). \[ R\equiv\equiv H \rightarrow \]

(c). \[ R\equiv\equiv H \rightarrow \]

(d). \[ R\equiv\equiv CH_3 \rightarrow \]

(e). \[ R\equiv\equiv H \rightarrow \]

(f). \[ R\equiv\equiv H \rightarrow \]

More information about addition to alkynes can be found in Chapter 9 of your textbook, sections 9.9-10. Additional problems on addition reactions include those problems within the above section.
APPENDIX E

ASSESSMENT QUESTIONS
<table>
<thead>
<tr>
<th>Topic</th>
<th>Occasion</th>
<th>Assessment</th>
<th>Instructor’s Activity</th>
<th>Type</th>
<th>Variables Collected</th>
<th>Achievement</th>
<th>Concept Integration</th>
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<td>1st Activity</td>
<td>3A Clicker</td>
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<td>AB1a</td>
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<td>Final Exam</td>
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*not collected due to end of semester
Assessment AB1a &AB1c (Activity 3A – First Acid Base Activity)

Achievement:

Given the pKa’s shown below, predict the position of equilibrium for this reaction.

\[
\begin{array}{c}
\text{H}_3\text{C} \quad \text{C} \quad \text{C} \quad \text{O} \\
p\text{Ka}=20 \\
\quad \text{H} \quad \text{H} \\
\text{H}_2\text{O} \\
p\text{Ka}=16 \\
\end{array}
\quad \begin{array}{c}
\text{H}_2\text{O} \\
p\text{Ka}=16 \\
\end{array}
\]

A. more products than reactants
B. more reactants than products
C. 50% products and 50% reactants
D. not sure how to predict

Concept Integration:

What is the best reason for your answer to the previous question predicting the equilibrium of the reaction shown?

\[
\begin{array}{c}
\text{H}_3\text{C} \quad \text{C} \quad \text{C} \quad \text{O} \\
p\text{Ka}=20 \\
\quad \text{H} \quad \text{H} \\
\text{H}_2\text{O} \\
p\text{Ka}=16 \\
\end{array}
\quad \begin{array}{c}
\text{H}_3\text{C} \quad \text{C} \quad \text{C} \quad \text{O} \\
p\text{Ka}=16 \\
\quad \text{H} \quad \text{H} \\
\end{array}
\]

A. The reactant is the stronger the acid because it has the larger pKa
B. The products shown are the weaker acid and base
C. The difference in the pKa’s of products minus reactants is negative
D. At equilibrium there is an equal amount of reactants and products
E. I am not sure
F. I ran out of time
Achievement:

Rank the numbered hydrogen atoms in order of decreasing acidity (most acidic is first). Your answer should be a 5-digit number where the most acidic hydrogen is the first digit in your answer.

Concept Integration:

What was the theoretical reason for your choice of the most acidic hydrogen in the previous question?

a) electronegativity effect
b) inductive effect
c) resonance stabilization of conjugate base
d) formal charge effect
e) polarizability
Assessment Questions NS1a & NS1c (Activity 9A – First Nucleophilic Substitution Activity)

Achievement:

The SN2 transition state is drawn below. (The direction the transition state is written does NOT indicate the reactants or products in this case.)

First number: In the ts, which of the following would be the nucleophile?
1. Cl-
2. -OCH₃
3. -CH₃

Second number: In the ts, which of the following would be the leaving group?
4. Cl-
5. -OCH₃
6. -CH₃

Concept Integration:

Which explanation(s) support(s) that -OCH₃ is the nucleophile and Cl- is the leaving group? Enter all numbers that are correct OR # 6 for “I don’t know why”.

1. The pKa for HCl (<0) is lower than CH₃OH (~16).
2. The lone pair on Cl- is more stable than the lone pair on -OCH₃, so Cl- is a lower energy product.
3. Both can be nucleophiles but -OCH₃ is a stronger base than Cl-.
4. The bond between C and -OCH₃ is stronger than the bond between C and Cl-
5. CH₃OH and Cl- are lower in energy than CH₃Cl and OH
6. I don’t know why
Assessment Questions NS2a, NS2c, N5da & NSdc (Activity 9B – Second Nucleophilic Substitution Activity)

Achievement:

By what mechanism would this reaction proceed?

A. SN1
B. SN2
C. E1
D. E2
E. SN1 and E1

Concept Integration:

Why does a weak Nu/Base favor a unimolecular (SN1/E1) mechanism? (enter numbers for all statements which are correct reason(s) or enter 6 for “I don’t know”.

1. The cationic intermediate is unstable and will react even if the Nu/Base is weak.
2. A Nu/Base can be weak because it does not need to help push out the leaving group.
3. A protic solvent H-bonds with the Nu/base by hydrogen bonding to it, making it weaker.
4. The concentration of the Nu/Base is not a factor in unimolecular reactions.
5. A sterically hindered Nu/Base does not affect unimolecular reactions.
6. I don’t know.
Assessment Questions EA1a &EA1c (Activity 12B – First Electrophilic Addition Activity)

Achievement:

Which statement best describes the reaction below?

A. Everything is correct
B. Incorrect stereochemistry
C. Incorrect regiochemistry
D. Incorrect stereochemistry and regiochemistry
E. I don’t know

Concept Integration:

Which of the following statements describes the reason(s) for your answer? Input all that apply.

1. The Nu° Br bonds to the most substituted carbon.
2. SYN addition gives the CIS product.
3. Only one enantiomer is a product.
4. The Nu° H2O bonds to the most substituted carbon.
5. ANTI addition gives the TRANS product.
6. I don’t know.
Assessment Questions EA2a &EA2c (Activity 12C – Second Electrophilic Addition Activity)

Achievement:

Which is the major product for this reaction?

![Reaction diagram]

Concept Integration:

What are the reason(s) for your answer? Choose all that apply.

1. The nucleophile is H2O.
2. The nucleophile attacks the least substituted sp C.
3. The nucleophile attacks the most substituted sp C.
4. Because a double bond is made, the nucleophile adds a second time.
5. The enol is less stable than the keto form.
6. I don’t know.
First Midterm Exam Question on Acid Base Topic

For the following reaction:

(Eq 1) $\text{H}_3\text{C}^\equiv\text{N}^+\text{H}^+ + \text{OH}^- \rightleftharpoons$

(Eq 2) $\text{H}_2\text{C}^\equiv\text{N}^+\text{H}^+ + \text{OH}^- \rightleftharpoons$

Achievement:

(a). (6 pts) Draw all the expected products for each of the above reactions, including curved arrows to show electron movement.

(b). (3 pts) Draw any resonance structures of the above products.

(c). (2 pts) Indicate whether equilibrium favors the reactants or products for each reaction.
   - Eq 1 equilibrium favors ________________
   - Eq 2 equilibrium favors ________________

(d). (2 pts) Which reaction, Eq 1 or Eq 2, will produce the most products?

Concept Integration:

(e). (4 pts) Using the concepts related to stabilities of the conjugate base that apply to this reaction, explain your answers to (c) and (d). Be sure your explanation is clear and thorough, but concisely written using grammatically correct and complete English sentences.
Assessment Questions SN 4a & SN4c

Second Midterm Exam Question on Nucleophilic Substitution Topic

Achievement:

. (8 pts) a). Draw a complete mechanism for the following SN1 reaction. Use curved arrows to show electron movement and draw all expected products. (Be sure to include all intermediates, if any, and the appropriate stereochemistry.)

b). (2 pts) If there is more than one product, indicate which is the major product or if the products are formed in equal amounts.

6. The energy diagrams below illustrate a substitution reaction. The energy pathway for this reaction is shown as a solid line. The dotted lines on each diagram refer to one change made to the reaction in each of three experiments.

a). (2pts) Does the reaction proceed through an Sn1 or Sn2 mechanism?

Concept Integration:

b). (3 pts) Which energy diagram (if any) represents an increase in concentration of the CH3OH by a factor of 5 in the new reaction (dotted line)? Justify your answer.

c). (3 pts) Which energy diagram (if any) represents a change from CH3OH to NaOCH3 as the nucleophile in the new reaction (dotted line)? Justify your answer.

d). (3 pts) Which energy diagram (if any) represents a change from CH3CH2CH2Cl to CH3CH2CH2I as the electrophile in the new reaction (dotted line)? Justify your answer.

e). (3 pts) Which energy diagram (if any) represents a change from Et2O as a solvent to CH3OH as a solvent in the new reaction (dotted line)? Justify your answer.
Assessment Questions EA 4a & EA 4c

Third Midterm Exam Question on Electrophilic Addition Topic

Reaction A only gives one product. Reaction B produces the two products shown.

Achievement:

A. Draw curved arrows to illustrate electron movement for the first step in each reaction.

B. Draw the intermediate that leads to the product in the box directly above the product.

C. Draw resonance structures for the intermediates, if any.

Concept Integration:

D. Considering the intermediates for Reaction A, why is only one product formed?

E. Considering the intermediates in Reaction B, why are both products formed?
Assessment Questions Fa & Fc

Final Examination Written Free Response Question

The following reaction of an alcohol to an alkene is an E1 reaction. A proposed but incorrect mechanism is shown below; step 1 of the mechanism as drawn is unlikely.

Overall Reaction

![Overall Reaction Diagram]

Proposed Mechanism

![Proposed Mechanism Diagram]

Concept Integration:

(a). (2 pts) Explain why step 1 of the proposed mechanism is unlikely. Relate as many concepts as are appropriate (acid, base, nucleophile, electrophile, positive or negative charges, intermediates, lone pairs, etc.)

Achievement:

(b). (7 pts) Draw arrows to show electron movement for each step of the correct mechanism in the reaction below. (The atoms are numbered for the next question.)

![Mechanism Diagram]

Concept Integration:

(c). (4 pts) Using the atom numbers for reference, describe each step of the mechanism. Be sure to describe explicitly what happens with each arrow and the chemical basis for your reasoning.
REFERENCES


