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INVESTIGATING THE STUDENTS' UNDERSTANDING OF SURFACE PHENOMENA

By

KASTRO M. HAMED

B. S., Brigham Young University, 1989
M. S., University of Utah, 1991

A DISSERTATION

Submitted in partial fulfillment of the

requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Physics
College of Arts and Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1999

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ABSTRACT

This study investigated students' understanding of surface phenomena. The main purpose for conducting this research endeavor was to understand how students think about a complex topic about which they have little direct or formal instruction. The motivation for focusing on surface phenomena stemmed from an interest in integrating research and education. Despite the importance of surfaces and interfaces in research laboratories, in technological applications, and in everyday experiences, no previous systematic effort was done on pedagogy related to surface phenomena.

The design of this research project was qualitative, exploratory, based on a Piagetian semi-structured clinical piloted interview, focused on obtaining a longitudinal view of the intended sample. The sampling was purposeful and the sample consisted of forty-four undergraduate students at Kansas State University. The student participants were enrolled in physics classes that spanned a wide academic spectrum. The data were analyzed qualitatively.

The main themes that emerged from the analysis were: a) students used analogies when confronted with novel situations, b) students mixed descriptions and explanations, c) students used the same explanation for several phenomena, d) students manifested difficulties transferring the meaning of vocabulary across discipline boundaries, e) in addition to the introductory chemistry classes, students used everyday experiences and job-related experiences as sources of knowledge, and f) students' inquisitiveness and eagerness to investigate and discuss novel phenomena seemed to peak about the time students were enrolled in second year physics classes.

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CHAPTER ONE

SETTING THE STAGE

1.1 Integration of Research and Education

As modern science expands the frontiers of knowledge, and research laboratories constantly produce new discoveries, a parallel revolution in science education becomes an imperative that should not be overlooked. Unfortunately, science teaching has fallen far behind, and has not progressed at the same pace as scientific discoveries and research laboratories. Jack Wilson captured the essence of this theme eloquently when he said:

> "In 1988 it was noted that if one could bring James Clerk Maxwell back from the late 19th century into an introductory physics classroom of 1988, he would recognize nearly everything he saw. Yet, he would recognize almost nothing at any research meeting. This disparity between the "state of the art" in science and the "state of the art" in teaching prevailed in many disciplines. Content in each discipline needed to be updated to reflect modern issues and understanding. In addition, we needed to examine the introductory course in the light of what we are learning about the way students learn. Change, in physics, comes quickly, is readily communicated, and is widely appreciated. Change, in physics teaching, is long in development, is poorly communicated, and is often met with resistance." (Wilson, 1997).

Definitely, the disparity alluded to in the above quotation is an on going problem. However, the increased awareness for the importance of the integration of research and education was evident in the literature. Stanford University devoted an issue of the quarterly publication *Speaking of Teaching* to promote synergism between teaching and research. In that publication they promoted the idea that to discover knowledge and to communicate it to others were no longer regarded as separate activities. As Gerhard Casper, Stanford University President, noted that discovering knowledge and communicating it to others were two sides of the same coin: the search to know. The article went further to eloquently state that: "In general, research should be teaching-fed, and teaching should be research-led". Ernest Boyer at the Carnegie Foundation for the Advancement of Science Teaching 1990 special report, Scholarship Reconsidered: Priorities of the Professoriate outlined a broader vision for what the term *scholarship* should mean. He said:

> "We believe the time has come to move beyond the tired old "teaching versus research" debate and give the familiar and honorable term "scholarship" a broader, more capacious meaning, one that brings legitimacy to the full scope of academic work ... Specifically, we conclude that the work of the professoriate might be thought of as having four separate, yet overlapping, functions. These are: the scholarship of discovery; the scholarship of integration; the scholarship of application; and the scholarship of teaching."

Additionally, the issue of integrating research and education had received some attention from the National Science Foundation (NSF). In a recent report the Advisory Committee to the NSF Directorate for Education and Human Resources stated:

> "The NSF itself must reflect through its organization, its rhetoric, and its leadership activities, a holistic approach to undergraduate SMET (Science, Mathematics, Engineering, and Technology) education. Its directorates must continue their good work to integrate research and education, while the Directorate for Education and Human Resources continues to provide overall leadership." (NSF, 1996).

In keeping with the spirit of that recommendation, a select group of ten universities have been chosen for the National Science Foundation first-ever Recognition Awards for the Integration of Research and Education (RAIRE). The awards recognized demonstrated leadership, innovation and achievement in developing programs institution-wide which integrated research and education activities. Grants given under the Recognition Awards were for three years, at $500,000 each. The Universities which received the awards were The University of Arizona, The University of California-Los Angeles, Carnegie Mellon University, The University of Delaware, Duke University, Kansas State University, The University of Michigan, The University of Missouri, The State University of New York at Stony Brook, and The University of Oregon.

Examples of endeavors related to the Integration of Research and Education at Kansas State University included the Visual Quantum Mechanics, the Genetics Education program, and the education of a better–prepared generation of K-12 teachers. In the

Visual Quantum Mechanics project several instructional units were developed to introduce quantum physics to students who did not have a background in modern physics or higher level math. The primary target audiences for these materials were the high school students. To reach these students, the instructional units integrated interactive computer programs and digital multimedia with inexpensive experimental materials and written documents in an activity-based environment. Each of the instructional units was field tested and evaluated. The Genetics Education program was initiated in 1988 as a two-year teacher enhancement program funded by National Science Foundation. The goal of this project was to help teachers with diverse backgrounds and teaching responsibilities acquire the knowledge and materials needed to teach technical, quantitative, and interdisciplinary science by using experimental procedures from current genetics research. The central strategy was to establish a network among teachers, science education specialists, and research scientists. The third example of integration efforts was the development of A Model Science and Mathematics Curriculum for Elementary Education Students that involved faculty from four science departments, mathematics, and the College of Education. It incorporated recent scientific research and had a component in which the elementary education majors actively engaged in research as a way of learning about science, mathematics, and teaching.

Continuing on the same line on integration, we are developing a more advanced version of Visual Quantum Mechanics that could be used in the standard university classes of Modern Physics. Also, we are interested in investigating the possibility of bringing contemporary research topics to undergraduate students in physics, and in the possibility of getting more undergraduate physics students, and future science teachers involved in the research laboratories. One of the topics that we are currently focusing some of our efforts on is contemporary research in surface science, a topic which has been traditionally reserved for much later, if ever, in the student's education. However, in keeping with constructivism, knowing where our students are, in their knowledge and understanding, is an important step before developing instructional materials. This probing into students' understanding of surface phenomena is the focus of this dissertation project.

1.2 The Ubiquity of Surface Phenomena and Their Applications

Surfaces and surface phenomena are everywhere, and play an important role in nature. Important processes such as the exchange of air, water, and nutrients between the surroundings and the living organism take place at surfaces or buried interfaces. These physico-chemical systems can only be explained once the complex processes occurring at these surfaces and interfaces are themselves understood. Most of our interactions with matter take place at the surface. Since every material communicates with the external world primarily through its surface, the study of surface interactions is of paramount importance to a complete understanding of materials behavior and their potential usage.

Surfaces with specially designed functional properties are also an important issue in the development and production of industrial components and systems. Technical, economic, and ecological constraints are making the demands on industrial products ever more complex. The design challenge can only be met by taking a holistic approach to the problem, in which both the desired bulk properties and the desired surface properties are simultaneously taken into account. Nowadays surface technology has to be a primary factor in the design of many industrial products, and is often responsible for a significant proportion of their added value. Surface technology is intimately linked with Life Cycle Engineering and the environment. The quality and durability of industrial products are often determined (sometimes exclusively) by the changes in the surface structure or composition during the products lifetime. Examples of such undesirable changes include wear (tribology), corrosion, and bio-incompatibility of medical devices.

Optimal solutions to materials problems often involve a choice of different substances for the bulk materials and the surface layers. For this reason researchers find themselves dealing with composite materials, such as metal-polymer, metal ceramic, or polymer-ceramic systems. The interfacial properties of these materials (e.g. adhesion, corrosion resistance) are particularly critical.

Nanotechnology, developed in the wake of the newly invented scanning probe methods, has presented the field of surface technology with a whole new realm in which to operate, and these new analytical methods give us a much clearer window onto nanoscale surface structures. Tailored micro- and nano-engineering of materials is an area of tremendous potential, as is the extension of our knowledge of nano-composition of surfaces and their use in nanochemical processes (e.g. in catalysis). Somojai (1996, & 1998) described some of the details and applications of catalysis. Somorjai's examples included applications to the automobile industry, such as the three-way catalytic converter utilized to clean automobile exhaust and to make it more environmentally friendly. Other examples of catalysis that have been investigated by surface science were the bimetallic platinum-based catalysts (Pt-Re, Pt-Ir, and Pt-Sn) have great applications in the high-octane fuel producing technology.

The computer industry is another example where surface science plays a great role. Semiconductor-based technologies are at the heart of computer manufacturing. The fabrication of microelectronic circuits often involves layer-by-layer deposition of semiconductor (Si, GaAs, etc.), metal (Al, Cu, etc.), and insulator (SiO_2, polymer) thin films, in various configurations. The film thickness of each of these materials is at present in the $10^2 - 10^3$ Å range (Evans, 1999), and these layers alternate in both two and three dimensions. The fabrication of these layers is carried out by surface processes using chemical vapor deposition, sublimation, or sputter deposition from a radiofrequency plasma. The nucleation and growth mechanism are monitored by surface science techniques such as reflection high-energy electron diffraction (RHEED) and electron microscopy. Making ohmic contacts to semiconductor devices often involves the formation of surface compounds; that is, materials with a two-dimensional phase diagram that is very different from their bulk phase diagram. Transition metal silicides are used to obtain desirable electrical properties at metal-semiconductor contacts (Somorjai, 1996).

Another computer related application which Somorjai (1996) presented was the disk drive magnetic storage. Information in a computer is usually stored on a hard disk (ceramic or glass) that is coated with a thin magnetic film (≤1000 Å) made from a mix of transition metal oxides. The film is then coated by a sputtered carbon film (~200 Å thick) that contains various amounts of hydrogen which is then lubricated by a monolayer of high molecular weight polyfluoro ether. The drive moves the tip of a magnetic material over the disk at high speed to transmit a magnetic signal, thereby storing or retrieving information on the disk. The closer the tip tracks the disk, the higher the density of information that can be stored. In 1996, the gap between the tip and disk was about 200 Å and the tip velocity was a few meters per second. Such a surface and interface device poses unique challenges to surface scientists and will be the focus of frontier research studies for many years to come (Somorjai, 1996).

The medical applications of surface science are numerous. Special-purpose metal alloys and polymer coatings are used to prevent the body from rejecting prosthetic bone replacements. With over 200,000 hip replacements performed in the United States each year, the importance of such materials is evident. (CCMMP, 1997). Also, using advances in cellular and molecular biology and surface characterization techniques, researchers are probing both synthetic and native biomaterials with more rigor than ever before. And they are applying the insights provided by biology to better engineering and design. Because a lot of the biological response to any implanted material is determined by both the chemistry and the morphology of the surface, how the surfaces of biomaterials interact with the body is receiving much scrutiny. Many researchers believe that understanding surfaces is key to the design of clinically useful materials. For example, research in the laboratory of Professor Leckband at the University of Illinois, Urbana-Champaign, aims to identify the molecular basis of adhesion and molecular recognition at membrane surfaces through direct force measurements, as well as surface, analytical, biochemical, and cell biophysical methods. And at the University of Heidelberg, Germany, Professor Grunze and colleagues are working on a general model to explain and predict the nonspecific interactions of surfaces with proteins and other biologically relevant molecules (Rouhi, 1999).

1.3 Motivations

Considering the fact that the existing curricula already have a lot of material to cover, what would be the motivation for adding the study of some surface phenomena to the undergraduate curriculum? Actually several motivations exist.

First, there are many examples of and applications of surface phenomena in everyday encounters. The concreteness of the experience can provide a solid base to build further formal learning and reasoning. Drawing on familiar experiences can be very helpful. It was said that "Discovery consists of seeing what everybody has seen and thinking what nobody has thought."

Second, the study of surface phenomena is inherently multidisciplinary and brings several fields of inquiry together. This multidisciplinary nature of the topic can serve in assisting the student see some of the connections among the fields of knowledge, and build bridges which can have productive consequences to the student's own cognitive structure.

Third, most of the discussion about surface phenomena is still in the stage of development, and computational, experimental, and theoretical studies of surfaces are an on going endeavor. Thus, studying surface phenomena can provide the students with a first-hand experience of how science is developed.

Fourth, Being involved with science as outlined in the previous point is a productive experience not only for the general public and the future scientists, but also for the future science teachers who can greatly impact the learning and attitudes of the future generations of students. When the teachers themselves have experienced the process of scientific discovery and debated issues at the cutting edge of knowledge, their teaching approach will become more productive and positive. Some researchers advise teachers explicitly to introduce frequently novelty and information that cries out for explanation as away to increase motivation to learn (Byrnes, 1996).

Fifth, the wealth of technological applications of surface phenomena and surface science can in itself be a motivation for studying the topic. In section 1.2 I outlined a few prominent technological examples such as computer and medical applications that make extensive use of ideas developed in the laboratories of surface sciences.

1.4 Research As A guide for Curriculum Development

1.4.1 Examples from the Introductory Physics Course

The maxim: "In general, research should be teaching-fed, and teaching should be research-led", should be put to use in the development of future curricula which bring closer the "state of the art" in physics and the "state of the art" in physics teaching. Several physics education researchers have set forth to use research as a guide for curriculum development.

Guided by the research findings related to students' reasoning, conceptual understanding, and the ineffectiveness of the current mode of instruction to reach more than a tiny fraction of the students (McDermott, 1991; Hesteness, 1992; Hake, 1996), several strategies for teaching were created (Scott, Asoko, & Driver, 1992).

Additionally, researchers in physics education created many innovative curricula and teaching methods. Examples of these curricula include Visual Quantum Mechanics by Zollman; Workshop Physics by Laws; Physics by Inquiry and Tutorials in Introductory Physics by McDermott; Overview Case Study by Van Heuvelen; Spiral Physics by D'Alessandris; Peer Instruction by Mazur; Interactive Lecture "Tools" by Beichner; Tools for Scientific Thinking and Real Time Physics By Thornton & Sokoloff, Electric & Magnetic Interactions by Chabay & Sherwood; Understanding Basic Mechanics by Reif; Concept Based Problem Solving by Mestre & Gerace; and Socratic Dialogues by Hake (O'Kuma, 1997).

1.4.2 Connections to This Research Project

This research project follows the tradition of constructivist epistemology where students' current understanding is of paramount importance to what they can learn. In that spirit, students' ideas about some surface phenomena will be elicited and analyzed. Guided by the findings of the research, some instructional materials will be created to introduce undergraduate physics students to the ideas of surface science. This effort will hopefully assist in bridging the gap between the "the state of the art" in physics research and the "state of the art" in physics teaching, and be a successful model for the integration of research and education.

1.5 Research Purposes

The main purpose for conducting this research endeavor is to understand how students think about a complex topic about which they have little direct or formal introduction. Consequently the findings of this project can serve two other purposes:

1. Potentially serve as a first phase in a three-phase project. The three phases being:
    a. Investigation of students' conceptions of surface phenomena.
    b. Development of some instructional materials to assist the students in learning about surface phenomena and their applications.
    c. Evaluation of the pedagogical effectiveness of the instructional materials.
2. Potentially serve as a guide in the development of written, streamlined, research instruments similar to the FCI (Force Concept Inventory), where the material to be investigated will focus on surface science concepts.

1.6 Research Questions

The research questions stemmed mostly from attempting to operationalize the research purposes that I stated above, and were refined iteratively as data were collected and analyzed.

1. What sources of knowledge do students rely on as they describe and explain surface phenomena?
2. Do patterns for the reasoning ability and inquisitiveness of students change during their undergraduate years of study (with some special focus on physics students at Kansas State University).
3. How predisposed are science students (physics majors in particular) to use microscopic explanations to describe and explain macroscopic phenomena?

4. Do students utilize what they were taught in formal settings (classes) to describe and explain familiar phenomena about which they have not learnt in classes?
5. What themes emerge from students' answers to the interview questions that are going to be the main instrument in this investigation?

CHAPTER TWO

CONCEPTUAL CONTEXT

Introduction

During the last thirty years, researchers have generated a considerable amount of knowledge about student learning. Accompanying this flood of knowledge, and perhaps partially responsible for its creation, was the paradigmatic shift of emphasis from the behaviorist view to the cognitive view of learning. New curricula emphasizing meaningful learning, and encouraging stepping higher on the ladder of Bloom's taxonomy were created. According to Bloom's taxonomy there are several levels for interacting with instructional material (Clegg, 1995). The lowest level on Bloom's taxonomy is shown when the learner memorizes, recalls, and repeats facts. The second level consists of the learner restating, recognizing and describing the memorized facts. The third level is manifested with the learner applying the learned facts. The fourth level is reached when the learner becomes able to analyze, and debate the facts. The fifth level is achieved when the learner becomes able to synthesize and assemble factual knowledge, and design experiments related to the facts being learned. The sixth level is reached when the learner becomes able to evaluate, judge and critique the facts.

Constructivism, as a theory of knowledge and knowing was the central piece that tied most of this cognitive movement together. In this study, I adopted Constructivism as a framework, then I established some connections between previous cognitive studies related to reasoning and conceptual understanding to this research study.

2.1 Constructivism as a Framework

Constructivism is a way of knowing and learning (Glasersfeld, 1996). As a theory, constructivism describes the nature of knowledge and how an individual acquires it. Tobin and Lorsbach (1992) define constructivism as: "... an epistemology, a theory of knowledge used to explain how we know what we know." Constructivism as an epistemology explains the relationship between knowledge, what we know, and the different forms of reality (Gallagher & Reid, 1981).

Although constructivism has found its way to science education only recently, the roots of the constructivist philosophy are more than two thousand years deep. Glasersfeld (1989) states that:

> The original seed of constructivists' ideas was undoubtedly the skeptics' realization that we can have no certain knowledge of the real world, because even if we could discover how our knowledge is derived from experience, there is no way of discovering how our experience might be related to what there is before we experience it. This realization is inherent in some of the fragments of the pre-Socrates from the 6th century B. C.

Also, the ideas of constructivism can be found in Arabic philosophical poetry, as in the following poem by Khalil Gibran:

> Then said a teacher, Speak to us of Teaching.
>
> And he said:
>
> No man can reveal to you aught but that which already lies half asleep in the dawning of your knowledge.

> The teacher who walks in the shadow of the temple, among his followers, gives not of his wisdom, but rather of his faith and his lovingness.
>
> If he is indeed wise he does not bid you enter the house of his wisdom, but rather leads you to the threshold of your own mind.
>
> The astronomer may speak to you of his understanding of space, but he cannot give you his understanding.
>
> The musician may sing to you of the rhythm which is in all space, but he cannot give you the ear which arrests the rhythm, nor the voice that echoes it.
>
> And he who is versed in the science of numbers can tell of the regions of weight and measure, but he cannot conduct you thither.
>
> For the vision of one man lends not its wings to another man.
>
> And even as each of you stands alone in God's knowledge, so must each one of you be alone in his knowledge of God and in his understanding of the earth. (Bell, Watts, & Ellington, 1984)

The constructivist view of learning stands in sharp contrast to what can be called the objectivist view of learning (Cobb, Yackel & Wood, 1992; Pirie & Kieren, 1992; Stofflett, 1994; Roth, 1994; Byrnes, 1996). Objectivists believe that knowledge can exist outside the mind of the knower and that learning is simply the process by which this externally real knowledge is transferred rather directly to the knower's mind. In this immediate acquisition conception, there is no reason students should have trouble learning anything. Moreover, it is assumed that what students get out of a lecture or lab is what is contained in the lecture or lab (fact for fact) and that all students can acquire the same information (Pressley et al. 1994). In contrast, constructivists believe that knowledge has no existence outside someone's mind and that students always interpret what is presented to them using their preexisting knowledge, histories, and typical ways of perceiving and acting (Pirie & Kieren, 1992). Because students often have unique experiences and histories, constructivists expect that students will develop idiosyncratic understandings of the same materials that differ from the understandings of experts in the field. Also, constructivists believe that students take what they can from a lecture or experience and use the partial understandings that are gleaned to build more complete and accurate understandings over time (Byrnes, 1996).

Knowledge remains the core of many epistemological debates. According to Staver (1986), whether our knowledge conformed to objects or objects conformed to our knowledge is an issue for epistemological discussion. Knowledge has been viewed primarily in a base of common-sense belief that a real world exists regardless of whether we take interest in it or even notice it. This realist perspective assumes that we come into the world as discoverers who build copies or replicas of reality in our minds (Bonder, 1986). As a result of the realist assumption, knowledge is viewed as something which could be transferred intact from the mind of the teacher to the mind of the student. Staver (1986) described the pervasive way of teaching as:

> "We tried valiantly to pour knowledge into youngsters' heads in the great empiricist tradition. In doing so, we have come to realize that the kind of knowledge described by Piaget is acquired in a very different way. It is constructed by children from previous knowledge and interaction with their environment."

Constructivism assumes that knowledge is actively built up by the learner through a process of construction or interpretation in a way that fits his or her own world (Glasersfeld, 1989). So students learn by trying to fit what they are taught to their own worlds. Learning from a constructivist perspective is the production of self-organization. Glasersfeld (1996) sums up what constructivism, may suggest to educators:

> "The art of teaching has little to do with the traffic of knowledge, its fundamental purpose must be to foster the art of learning."

And Redish (1994) clarifies what constructivism implies to a physics teacher by saying:

> "All you can do as a teacher is to make it easier for your students to learn. Of course, facilitation can be critical to the learning process. Constructivism should not be seen as disparaging teaching, but as demanding that we get feedback and evaluations from our students to see what works and what does not. It asks us to focus less on what we are teaching and more on what our students are learning."

2.2 Cognitive Development

In this context, the word *cognitive* is used to imply that the focus is on mental processes such as thinking, learning, remembering, and problem solving (as opposed to other psychological constructs such as emotions friendships, and personality traits). The word *development* is used to imply that cognitive processes change with age or experience (usually for the better) (Byrnes, 1996).

Over the last 100 years, many theories of cognitive development and learning have been proposed (Byrnes, 1996). However, those theories that have shaped contemporary research in science learning and reasoning are limited in number. A theory qualifies to have shaped contemporary educational research if educational researchers have recently used it to (a) interpret developmental or individual differences among students or (b) design new experiments (Byrnes, 1996). The five main theories of cognitive development and learning are: Thorndike's Theory, Piaget's Theory, Schema Theory, Information Processing Theory, and Vygotsky's Theory. Three themes emerge from the theories: practice is important; learning should be meaningful; and the knowledge students bring to the classroom can greatly affect what they learn. Reif (1984) has described education, as it occurs in and out of the classroom, as a process that produces a transition between some initial state of the student's knowledge and some desired final state. Cognitive research tries to understand the nature of the initial state (the student as he or she enters our class), the processes of teaching and learning by which a transition can be brought about, and the nature of the goal state, which is ideally expertise (Mestre, & Touger, 1989). Depending mostly on the information contained in (Byrens, 1996) I have created Table 2.1 to summarize and compare among the main theories of cognitive development.

Table 2.1

Summary of Theories of Cognitive Development and Learning

	Thorndike	**Piaget**	**Schema**	**Information Processing**	**Vygotsky**
Nature of Knowledge	Association between situations and responses	Constructivist, described knowledge in terms of schemas, concepts, and structures.	Existence of knowledge structures called schemata in two forms (objects and events)	Two forms of knowledge: declarative, and procedural.	Knowledge is described in terms of concepts and functions.
Learning and Knowledge Growth	According to the laws of exercise and effect. According to this way, repetition is very important for achieving the goals.	Knowledge is manifested in four levels of thought (sensorimotor, pre-operational, concrete operational, and formal operational) and grows through processes of abstraction, assimilation, accommodation, equilibration.	Schemata are formed through an abstraction process and can change in response to experience.	Knowledge acquisition is described as information passing through three memory stores: Sensory store, then short term store, then long term store.	Knowledge acquisition is described as a process of internalizing the words and actions of teachers, parents, and more competent peers.
Student Learning	Students are Viewed more as "other regulated than "self-regulated"	Adaptation of the newly acquired ideas and knowledge to the existing ones. Also, self-regulation.	Adaptive students acquire schemata and modify them based on experience.	Adaptive students use strategies to create permanent memories and monitor their performance	Adaptive students use egocentric speech and inner speech to help themselves stay on track.

2.2.1 Implications of Cognitive Theories for Physics Teaching and Learning

Redish (1994) remarked that during the past decade, data had accumulated which demonstrated that as physics teachers we failed to make an impact on the way a majority of our students thought about the world (Arons, 1990; Trowbridge, & McDermott,1980; Halloun, & Hestenes, 1987; Thornton, & Sokoloff, 1990, McDermott, 1991). Then, Redish (1994) argued that we must treat the teaching of physics as a scientific problem, and gave four broad principles with elaborate details and corollaries.

The first principle states that people tend to organize their experiences and observations into mental models. Mental models have several properties. First, they consist of propositions, images, rules of procedures, and statements as to when and how to be used. Second, they may contain contradictory elements. Third, they may be incomplete. Fourth, people may not know how to "run" the procedures present in their mental models. Fifth, elements of a mental model do not have firm boundaries; similar elements may be confused. Sixth, mental models tend to minimize expenditure of mental energy. According to this view of mental models, the goal of physics teaching is to have students build the proper mental models for doing physics and to develop the ability to reason qualitatively about physical processes.

The second principle is that it is reasonably easy to learn something that matches or extends an existing mental model. Therefore, mental models are not only the way we organize our interactions with the world, but they also control how we incorporate new information and experiences. This principle implies that new information should always be presented in a context that is familiar to the learner and that the context should be established first. Also, the use of analogies can be very useful in building needed conceptual bridges. For example, many students do not believe that a table exerts an upward force on a book that is resting on it. However, they are likely to believe that, if you press down on a spring, the spring exerts an upward force on your hand. A set-up involving a conspicuously springy table can bridge the gap between the two analogous (i.e., analogous to the physicist) situations (Mestre, & Touger, 1989).

The third principle states that it is very difficult to change an established mental model substantially. In order to change an existing mental model, the proposed replacement must be understandable, plausible, useful, and show that there is a strong conflict with the predictions based on the existing model.

The fourth principle states that since each individual constructs his or her own mental model ecology, different students have different mental models for physical models and different mental models for learning. One implication of this principle is that different students can have different reasons for giving the same answer. A second implication is that people have different styles of learning. A third implication is that there is no unique answer to the question: What is the best way to teach a particular subject? A fourth implication is that as physicists and people who have devoted significant portions of our lives to the learning of physics, our own experiences may be a very poor guide for telling us what to do for our students. A fifth implication is that the information about the state of our students' knowledge is contained within them. If we want to know what they know, we not only have to ask them, we have to listen to them.

2.2.2 Connections to This Research Project

From the preceding discussion, the importance of probing students' mental models and understanding becomes evident. Knowing where the students are in their development of mental models, students' sources of knowledge about the subject, and how the students reach their conclusions are the bases for helping the students build and improve their mental models. The interviews I conducted with students were all about listening to the students articulating, in their own words, their mental models regarding surface phenomena. Also, these interviews showed a dynamic model of the students' mental pictures that got stretched and expanded.

2.3 Development of Reasoning

Development of reasoning has been a central goal in many curriculum reform efforts. Arons (1997) states that:

> No curricular recommendation, reform or proposed structure has ever been made without some obeisance to the generic term "critical thinking" or one of its synonyms. The flood of reports on education in our schools and colleges that has been unleashed in recent years is no exception; every report, at every level of education, calls attention to the enhancement of thinking-reasoning capacities in the young.

But what is reasoning? And how does reasoning develop? Also, what are the characteristics of the stages of reasoning development? Then, how is the development of reasoning related to physics teaching in general and to this research project in particular? The answers to these important questions are the subject of many research papers and publications.

Reasoning is defined as the drawing of inferences or conclusions from known or assumed facts; the use of reason (Webster, 1997). Piaget studied the development of reasoning and characterized human intellectual development in terms of four stages (Inhelder & Piaget, 1958). The first two, called sensory-motor and preoperational, are usually completed when a child is seven or eight years old. Following these are two stages of logical operations, called concrete thought and formal thought (Karplus, 1977). Piaget has ascribed the process whereby individuals advance from one stage to the next to four contributing factors: maturation, experience with the physical environment, social transmission, and equilibration. The last item designates an internal mental process in which new experiences are combined with prior expectations and generate new logical operations (Karplus, 1977). It was hypothesized that each of Piaget's four stages serves as a precursor to all succeeding stages, so that reasoning develops sequentially, always from the less effective to the more effective stage, although not necessarily at the same rate for every individual. Also, the development of a person's reasoning should be thought of as gradual, and progressive (Fuller, Karplus, & Lawson, 1977).

From the research of Piaget and others Karplus (1977) has formulated certain rules for identifying reasoning patterns as belonging to concrete or to formal thought. In general, reasoning that makes use of direct experience, concrete objects, and familiar actions is classified as a concrete reasoning pattern. On the other hand, reasoning that is based on abstractions and that transcends experience is classified as a formal reasoning pattern. Here is a more extensive list of clues that are helpful in classifying reasoning patterns (Karplus, et al., 1977, Module 2).

When using concrete reasoning patterns, the individual:

C1: Applies classifications and generalizations based on observable criteria.

C2: Applies conservation logic- a quantity remains the same if nothing is added or taken away, two equal quantities give equal results if they are subjected to equal changes.

C3: Applies serial ordering and establishes a one-to-one correspondence between two observable sets.

When using formal reasoning patterns, the individual:

F1: Applies multiple classification, conservation logic, serial ordering, and other reasoning patterns to concepts, abstract properties, axioms, and theories.

F2: Applies combinatorial reasoning, considering all conceivable combinations.

F3: States and interprets functional relationships in mathematical form.

F4: Recognizes the necessity of an experimental design that controls all variables but the one being investigated.

F5: Reflects on his own reasoning to look for inconsistencies with other known information.

Table 2.2, which is borrowed from (Karplus, 1977), provides a summary comparing concrete and formal reasoning patterns.

Table 2.2

Concrete and Formal Reasoning Patterns

	CONCRETE	FORMAL
(a)	Needs reference to familiar actions, objects, and observable properties.	Can reason with concepts, relationships, abstract properties, axioms, and theories; uses symbols to express ideas.
(b)	Uses reasoning patterns C1-C3, but not patterns F1-F5.	Uses reasoning patterns F1-F5 as well as C1-C3.
(c)	Needs step-by-step instructions in a lengthy procedure.	Can plan a lengthy procedure given certain overall goals and resources.
(d)	Is not aware of his/her own reasoning, inconsistencies among various statements he/she makes, or contradictions with other known facts.	Is aware and critical of his/her own reasoning; actively seeks checks on the validity of his/her conclusions by appealing to other known information.

Piaget's original notion was that all persons use formal reasoning reliably by their late teens. Yet, some studies strongly suggested that, although almost everyone became able to use concrete reasoning, many people did not use formal reasoning reliably. These persons often appeared to be reasoning at formal level and/or comprehending formal subject matter when they were only applying memorized formulas, words or phrases (Fuller, Karplus, & Lawson, 1977).

In a series of articles addressing student patterns of thinking and reasoning Arons (1983 & 1984) discussed his observations and made a few recommendations. Arons observed that many students have great difficulty giving verbal interpretations of calculations. Instead, students take refuge in memorizing patterns and procedures of calculation rather than penetrating to an understanding and reasoning. For example, in discussing the concept of density, Arons noted that students have not separated the technical term from the verbal interpretation. He also noted that if he modified context slightly, students would experience difficulties, even if the required underlying reasoning remained the same. For example, when developing the concept of density with elementary school teachers he gave them the opportunity to measure volumes of irregular objects such as stones by displacement of water. After they performed such experiments, they were confronted with the question: "How would the volume of a piece of glass measured by displacement of water compare with its volume measured in kerosene? Explain your answer." To his surprise, he found many students sitting at the laboratory desk, struggling over this trivial question, and arguing in confused and pointless ways with their partners. Despite its importance, however, Arons notes that no documented empirical research was done to investigate in a systematic manner how students extrapolate from one context to another (Arons, 1997). Arons made some recommendations to assist the students attain more formal reasoning abilities (Arons 1976; 1982; 1983; 1984; & 1997). Here is a brief summary synthesized from Arons articles:

1. Exploratory activity and question asking should be given prior to concept formation and model building.
2. "Idea first and name afterwards", is a helpful approach to distinguish the concept interpretation from the technical name given to that concept.
3. Teachers should translate words into symbols and symbols into words, as in converting verbal problem statement into the corresponding arithmetical formulations; interpreting graphs and sketches.

4. Students should be taught to ask "How do we know...?", "What is the evidence for...?" Accepting the end result on faith because it was passed on to them by an authority is not sufficient, students should articulate in their own words the evidence and reasons that lead them to holding the views they exhibit.
5. Students should learn to distinguish between observation and inference. Also students should not rely merely on figurative or declarative knowledge, they should go beyond that to operative or procedural knowledge (Anderson, 1980; & Lawson, 1982).
6. Students should be assisted in developing the ability of hypothesis formation and testing, and to recognize when a crucial piece of data is missing.
7. Repetition is absolutely essential- not treading water in the same context until "mastery" is attained, but in altered and increasingly richer context, with encounters spread over time.

Another useful and well-supported account of reasoning abilities was developed by Kuhn (1989). Kuhn's model was also closely related to Piaget's work. By Kuhn's perspective, scientific reasoning involves and develops from abilities for argumentation, including abilities to identify and evaluate different points of view. She argues that these abilities are not involved in everyday thinking and that they are often not sufficiently developed in many children and nonscientist adults. Thus, for example, when asked to defend a conjecture against counter evidence, many students simply reiterate the conjecture; when asked to generate hypothetical, contradictory evidence (e.g., "What evidence might someone give to try to show that you were wrong?"), they are unable to answer appropriately. In general, they are unable to coordinate and distinguish alternative theories and evidence. Rather, they meld theory and evidence into single "script" they take for granted as describing reality (Hammer, 1996).

Connections to this Research Project

At this stage, I would like to draw some attention to the connections between the discussion of the development of reasoning and the current research endeavor. First, the issue of knowledge and reasoning transfer across boundaries of discipline and experience is of great importance, yet empirical research is needed to analyze how students make the transition (Arons, 1997). This current project collected data to assist in explaining how students manifest the knowledge transfer, and fill some of need which Arons alluded to. Second, in keeping with Arons recommendation for utilizing rich contexts, students were invited to manifest their reasoning about surface phenomena, and articulate the sources of their explanations. Third, the interview questions asked the students to describe and explain physical phenomena, and that provided us with a window to observe students' ability to distinguish between description and explanation. Fourth, I wanted to analyze whether students hide behind technical terms, or provide detailed explanations for the physical phenomena. These connections lead us to discuss conceptual understanding in more detail.

2.4 Conceptual Understanding and Conceptual Change

2.4.1 The Accumulating Research on Conceptual Understanding and Conceptual Change

Due to their importance in science teaching and learning, issues of conceptual understanding and conceptual change have received a considerable amount of attention from the science education researchers. According to radical constructivism (Glasersfeld, 1984) conceptions are fundamental beliefs about how the world works, which individuals form in response to experiences and in concert with others (Dykstra, 1992). It is a matter of what sense the student makes of the world rather than describing what the world is. This differs from the way the phrase alternative conception and its nominal synonyms -- alternative framework, student conception, naïve conception, misconception -- are used in the field. Quite often, however, research articles refer to the state of knowledge of students, or a response that is different from what is accepted by experts in the field as misconceptions or alternate conceptions.

Examples of misconceptions abound in the research literature (Mestre, and Touger, 1989). Several conferences have been devoted to the discussion of misconceptions. The two heavily attended international conferences on misconceptions at Cornell University in 1983 and 1987, with the latter meeting yielding three large volumes of proceedings, are clear examples (Helm & Novak, 1983; Novak, 1987). In addition to these general conferences, several specialized conferences were held. Each of the specialized conferences has been devoted to teaching and learning in a particular area of physics. In 1985 a conference on Teaching Thermodynamics was held in the United Kingdom (Lewins, 1985); in 1988 an international conference on Teaching Modern Physics was held in Germany (Luchner, Deger, Dengler, & Worg, 1988); in 1990 a conference was held in the Netherlands to discuss Relating Macroscopic Phenomena to Microscopic Particles as a central problem in secondary science education (Licht, & Waarlo, 1990); and in 1995 an international conference was held in Italy on Teaching the Science of Condensed Matter and New Materials (Michelini, Jona, & Cobai, 1996).

Also, several bibliographies, cataloging hundreds of articles related to students' misconceptions in science, have been produced. Among the most notable of these bibliographies are those of Pfundt and Duit (1987), the physics portion of this bibliography is included in Table 2.3; Maloney (1985); and Dykstra and Schroeder (1987). Also several models of conceptual change exist in the science education literature (Scott, Asoko, and Driver, 1992). Nassbaum and Novick (1982) encouraged students to exchange their existing ideas for entiely new conceptions. Brown and Clement (1989) encouraged students to develop a scientific understanding which may be held in parallel with existing notions. Niedderer (1987) encouraged the students to recognize the appropriateness and/or applicability of models in different situations.

Table 2.3

Studies on Student's Conceptions in Different Areas of physics
Bases on (Pfundt & Duit, 1987)

Subject	Number of Articles	Contents Cover
Mechanics	176	Force and motion/ work, power, energy/ speed, acceleration/ gravity/ pressure/ density/ floating, sinking.
Electricity	104	Simple, branched circuits/ topological and geometrical structure/ models of current flow/ current, voltage, resistance/ electrostatics/ electromagnetism/ danger of electricity.
Heat	47	Heat and temperature/ heat transfer/ expansion by heating/ change of state, boiling, freezing/ explanation of heat phenomena in the particle model.
Optics	40	Light/ light propagation/ vision/ color
Particles	39	Structure of matter/ explanation of phenomena (e.g. heat, states of matter)/ conceptions of the atom/ radioactivity.
Energy	27	Energy transformation/conservation, degradation.
Astronomy	19	Shape of the earth/ characteristics of gravitational attraction/ satellites.
Modern Physics	5	Quantum mechanics/ Special relativity.

West and Pines (1985) provide an interesting vine metaphor to explain conceptual learning. According to this metaphor, learning is the integration of the learner's intuitive view of the world and formal instruction (which they refer to as two sources of knowledge). West and Pines imagine two vines representing these different sources of knowledge. One vine originates from the learner's intuitive knowledge of the world (which they call the upward-growing vine to emphasize that this is part of the growth of the learner). The other originates from formal instruction (which they call the downward-growing vine to emphasize its imposition on the learner from above). Genuine conceptual learning involves the intertwining of these two vines. The postulated vine metaphor emphasizes that once integration occurs, the sources of particular parts of the intertwined vines are impossible to identify. Indeed, at this point, the question of sources may be irrelevant. At the point of integration, however, the sources of knowledge are most important.

2.4.2 The Particulate Nature of Matter and Micro-Macro Connections

The particulate nature of matter is the very essence of physics and chemistry. Feynman (1962) says:

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that *all things are made of atoms—little particles that move around*

> *in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into each other.* In that one sentence, …, there is an enormous of information about the world, if just a little imagination and thinking are applied.

Atomic behavior is an abstract, formal concept that is necessary to the understanding of many physical and chemical concepts. Within the last two decades there has been considerable interest among researchers in students' understanding of the particulate nature of matter. From the existing research literature, we know that students have difficulty understanding concepts involving the particulate nature of matter, and that this is an area of many student misconceptions (Dow et al., 1978; Novick and Nussbaum, 1978, & 1981; Mitchell and Kellington 1982; Mitchell, & Gunstone, 1984; Ben Zvi, et al, 1986, & 1989; Griffiths, & Preston, 1989; Haider, & Abraham, 1991; Scott, 1992; Gabel, 1993; Benson, 1993; Lee, 1993; Johnson, 1998; Fischler, & Peuckert, 1999). Yarroch (1985) and Gabel, Samuel & Hunn (1987) identify the inability of students to visualize particulate behavior as a possible source for this lack of understanding. Johnson (1998), however, argues that teaching might well be inadvertently promoting alternative ideas as endpoints in themselves

Shepherd and Renner found 50% of their 10th and 12th grade subjects held alternate conceptions concerning the structure of matter (Shepherd, & Renner, 1982). Osborne, Cosgove, and Schollum (1982) in their study of chemistry students in New Zealand schools found that students have difficulty in understanding that something which cannot be seen exists: e.g., a colorless gas in a test tube or a sugar dissolved in water. They suggested that teachers should help modify the misconception that substances must be visible to exist.

In a cross-age qualitative study involving elementary through college aged students, Novick and Nussbaum (1981) found that while older students do not overcome their alternative conceptions about the particulate nature of matter, concept understanding increased through the age levels. In this study the researchers asked open-ended questions and asked the students to make drawings along with the verbal answers. Sixty percent of the senior high school students did not picture empty space between gas particles, and more than fifty percent of these students did not show uniform distribution of gas particles in a closed flask. In addition, less than fifty percent of the high school and university students correctly indicated that the uniform particle distribution was due to constant particle motion. The study advised that teachers should be aware of such misconceptions by diagnosis and should use this knowledge in preparation of curriculum materials.

Osborne and Cosgrove (1983) used survey and interview techniques with subjects from ages 8 to 17 to probe the students' understanding concerning changes of state in water. Particular nonscientific ideas were seen in the responses of students from every age group, although the popularity of certain ideas changed with the age of the subjects. The survey results indicated that concept understanding generally increased with age.

A random sample of 300 fifteen year old students were asked to explain what happens to the particles in a block of ice when it is taken from the freezer at –10 °C and warmed to –1 °C (Brooks, Briggs, & Bell, 1983). These students from the Children's Learning in Science Project at the University of Leeds were asked to draw a diagram to aid their explanation. Nearly one-half used alternate ideas, and only 17% used particulate nature of matter concepts in an accepted way.

Abraham, Grzybowski, Renner, and Marek (1992) found that 86% of the 8th grade students in their study had no understanding or had developed alternate conceptions concerning the five concepts tested. In addition, only 2 of the 247 students used the terms "atoms" or "molecules" in their explanations of the concepts, even though these terms were used by their textbooks. This resistance to use particulate terminology may be linked to the inability to visualize particle behavior, which is a reoccurring finding.

De Vos and Verdonk (1987) found that high school students applied macroscopic reasoning to molecular behavior. Substance properties were applied to the molecule, i.e., molecules can be hard, liquid, opaque, or alive. The authors proposed that teachers develop curriculum materials covering chemical reactions which use the students' conceptions about the particulate nature of matter. Atomic theory, according to De Vos and Verdonk (1987), should be developed at a very simplistic level, initially from experimental data. Incremental advances in this atomic model toward a more scientific explanation of physical and chemical phenomena should be developed in response to students' questions and with students' input.

When investigating misconceptions held by 12th grade students, Griffiths and Preston (1989) found that five alternate conceptions were held more frequently by "academic science-oriented" students than "other" students in their study. Academic science students had overall averages of greater than 75% and at least 3 high school science courses. The academic science students believed that: (a) water molecules were composed of solid spheres (70% of science students vs. 15% of other students), (b) pressure affects the shape of the molecules (30% vs. 0%), (c) heat causes molecules to expand (30% vs. 5%), (d) the size of the atom depends on its number of protons (30% vs. 5%), and (e) atomic size is altered by collisions between atoms (40% vs. 5%). The authors attributed some of the alternate conceptions to instruction. What was of interest here was the fact that instruction possibly created some misconceptions.

Similarly, Peterson, Treagust, and Garnett (1989) in their study of high school chemistry students' understandings concerning covalent bonding and structure found instruction played a role in creating alternative conceptions. Research indicated that the subjects had not developed appropriate understanding of the concepts. Thirteen misconceptions were identified. For instance, 49% of the 159 11th graders tested believed that covalent bonds are broken when a substance changes shape, while the idea that equal sharing of the electron pair occurs in all covalent bonds was believed by 33% of the 11th graders and 23% of the 12th graders. Some of the alternate conceptions, the authors felt, could possibly be attributed to teachers not emphasizing the distinction between everyday and scientific meanings for some words. The word "share" in everyday sense means to equally divide, but in the chemical sense, a shared pair may not be equally situated between two atoms.

Formal thought was linked to the understanding of the particulate nature of matter in a study of preservice teachers (Gabel, Samuel, & Hunn, 1987). The subjects were given pictures of atoms and molecules represented by circles of various sizes and shades. They were then asked to draw a new picture of the resulting physical or chemical changes. Formal thought explained 28% of the variance in scores with 4% accounted for by the number of chemistry courses taken. The authors called for increased emphasis on the particulate nature of matter in introductory courses and the need to depict chemical phenomena in terms of the particulate nature of matter.

In their study of high school chemistry students, Haidar and Abraham (1991) found that students held many alternate conceptions concerning the particulate nature of matter. Many of the misconceptions were created by the students' application of macroscopic explanations from everyday experience to the concepts. For example, food coloring was often thought to color or paint the molecules of water in a question on dye diffusion in the same way ink stains or colors the students' hands. The authors found that in an attempt to simplify concepts requiring consideration of particulate matter, teachers and/or textbooks often used macroscopic explanations. The need for aids to appropriately link the macroscopic results observed in the laboratory with the microscopic, particulate nature of the physical and chemical processes was expressed.

Research has shown that visual aids and hands on activities can help in concept understanding (Tally, 1973; Holliday,1975; Cantu & Herron, 1978). Lee, et al. (1993) reported that students in the sixth grade performed significantly better on tests and interviews after using an activity based curriculum focusing on the particulate nature of matter. Gabel and Bruce (1991) used static visuals and reported increased understanding of the particulate nature of matter when the visuals themselves emphasized the particulate nature of matter. However, static visuals fail to depict the dynamic nature of many of the process. With the computer we now have the ability to provide three-dimensional, dynamic sequences of atomic and molecular behavior in contrast to the static two-dimensional models commonly used. The dynamic qualities of animation allow a more detailed view of atomic and molecular behavior to be presented. Zeilder and McIntosh

(1990) reported positive effects of the use of animations coupled with conceptual change strategies. Williamson and Abraham (1995) studied the effects of computer animation on the particulate mental models of college chemistry students and concluded that students who viewed the animations held a more particulate view of matter and had fewer misconceptions as a consequence.

2.4.3 Connection to the National Science Education Standards and Benchmarks

The National Science Education Standards (1996), and Benchmarks (1993) provide some guidance of the expectations for what content knowledge a student who had just finished high school should know. More explicitly The National Science Education Standards (1996) state that:

> High school students develop the ability to relate the macroscopic properties of substances they study in grades K-8 to the microscopic structure of substances. This development in understanding requires students to move among three domains of thought- the macroscopic world of observable phenomena, the microscopic world of molecules, atoms, and subatomic particles, and the symbolic and mathematical world of chemical formulas, equations, and symbols.

Also, according to the National Science Education Standards (1996) and Project 2061 "Benchmarks for Scientific Literacy" (1993), all students in grades (9-12) should develop an understanding of:

- Structure of atoms,
- Structure and properties of matter,

- Chemical reactions,
- Motions and forces,
- Conservation of energy and increase in disorder,
- Interactions of energy and matter.

The details of the content is then clarified and elaborated upon. Since this research study is focused on university students including those who are just starting, I could point out to how well incoming college students measure up to the relevant standards and benchmarks in the topics relevant to this study.

2.4.4 Connections to This Research Project

The potential for further investigations on the same lines is enormous. In carefully examining the research articles I found that many of them were a result of investigations done in a foreign country, with educational systems and curricula different from those in the USA, done with students in chemistry classes, or targeted middle or high school students. Similar explorations should be done to probe the understanding of college level physics students at various stages of their undergraduate studies of the particulate nature of matter.

In addition to emphasizing the particulate nature of matter when treating matter in its bulk form, surface phenomena and how students analyze these phenomena should receive more attention. Obviously, there is more to the surface than meets the eye, and many of the most important physical and chemical processes take place at the interface between two materials.

2.5 Physical Concepts Related to Surface Phenomena

The interview questions in this study covered a wide range of possible interfaces. Adamson (1990) characterized the possible interfaces between materials as: gas – liquid; gas – solid; liquid – liquid; liquid – solid; and solid – solid. I addressed the liquid – liquid interface via the question of oil spreading on water. This was not a new phenomenon. It was described in ancient times and was studied by Benjamin Franklin (Somorjai, 1998). The liquid – solid interface was introduced through discussing paint on a metal, and writing on paper with various kinds of ink. Then, the solid – solid interaction was discussed in the context of writing on paper with a pencil. The gas – liquid, and gas – solid interfaces were introduced via imagining at atom hitting these surfaces and the consequences of that on both the atom and the surface.

Many physical phenomena were introduced, and the underlying physical concepts were analyzed. Surface tension, adhesion, cohesion, dynamics of molecules in the surface of a metal as it gets exposed to heat, are topics of contemporary research (Rahman,1995). Surface tension has many far-reaching applications in biological and medical sciences (Rouhi,1999). Adhesion, friction, lubrication are of extreme importance in industry and many surface scientists are researching these phenomena, and collectively call them tribology. The dynamics of molecules on metal surfaces are being simulated via Molecular Dynamics and Monte Carlo techniques (Rahman, 1995).

The interest in analyzing structure and dynamics of surfaces grew dramatically in the last two decades with the advent of the Scanning Tunneling Microscope and nanotechnology. Within the Visual Quantum Mechanics, the Physics Education Research Group at Kansas State University prepared some instructional modules simulating how the Scanning Tunneling Microscope works.

CHAPTER THREE

METHODOLOGY

Introduction

While some authors of research methods referred to qualitative research methods as a paradigm (Creswell, 1998), others did not accept such a characterization, downplayed the difference between quantitative and qualitative methods, and viewed them as complementary (Krathohl, 1998). A paradigm is a much wider conceptual framework and view of the world that encompasses more than research methods. The second view sounded more consistent with the sense which Kuhn (1970) intended the word paradigm to convey. Qualitative research methods themselves were not a new paradigm. However, considering them acceptable and legitimate mainstream methods for generating credible knowledge was part of a new and evolving paradigm. This new paradigm was in harmony with, and possibly a direct fruit of, adopting post-positivist and constructivist epistemologies.

3.1 The Qualitative Approach

3.1.1 The Many Definitions of "Qualitative"

Although qualitative research methods have been around for a long time, the research community had not reached a unified definition of what was meant by *qualitative*. Some scholars were very reluctant to provide a definition and thought that all attempts to provide such a definition were foolhardy (Potter, 1996). Lincoln and Guba (1985) were proud of resisting a simple definition. In the preface of their book, they warned that readers would not find a simple direct definition. They said, "it is not possible to provide a simple definition.... Instead a proper impression...can be gleaned only as an overall perspective." Marshall and Rossman (1989) wrote an entire book on qualitative methods without defining "qualitative." Instead they said, "throughout the text we refer to *qualitative research* and *qualitative methods* as if these were one agreed-upon set that everyone understands." Denzin and Lincoln (1994) observed that "the field of qualitative research is far from a unified set of principles promulgated by networked groups of scholars" but that it was instead "defined primarily by a series of essential tensions, contradictions, and hesitations."

On the other hand, many scholars did present definitions of qualitative. Stauss and Corbin (1990) defined qualitative as "any kind of research that produces findings that are not arrived at by means of statistical procedures or other means of quantification." Jensen and Jankowski (1991) said that qualitative was concerned with "meaning in phenomenological and contextual terms." Jankowski and Wester (1991) said that, "the qualitative approach relies on an understanding of the meaning that people ascribe to their social and situation activities." Bogdan and Taylor (1975) maintained that the qualitative approach referred to research procedures that examined "settings and individuals within those settings holistically." Pauly (1991) saw qualitative as a five-step process: (1) finding a topic, (2) formulating research questions, (3) gathering the evidence, (4) interpreting the evidence, and (5) telling the researcher's story. Krathwohl (1998) noted that "qualitative research methods are particularly useful in understanding how individuals understand their world, in showing how individual's perceptions and intentions in situations determine their behavior, in exploring phenomena to find explanations, and in providing concrete and detailed illustrations of phenomena."

The research literature seemed replete with terms used as synonyms of the term "qualitative." Among the used terms were interpretive (Christian & Casey, 1989); humanistic studies (Lincoln & Guba, 1985; Jankowski & Wester, 1991); phenomenological (Bogdan & Taylor); naturalistic (Lincoln & Guba, 1985); hermeneutic (Christians & Carey, 1989; Lincoln & Guba, 1985); ethnography (Linfold & Meyer, 1987); ethnomethodology (Lindlof, 1991); critical theory and cultural science (Chistians & Carey, 1989); postpositivistic , subjective, and case study (Lincoln & Guba, 1985); interactionist (Jankowski & Wester, 1991).

Could we analyze all of the previous definitions and terms and assemble them into a single definition of qualitative? Potter (1996) stated that the result would truly be a cumbersome agglomeration, because there would be so many different synonyms, types of definitions, and organizational schemes to fit together. However, despite the reluctance of some scholars to provide a definition of *qualitative*, and the proliferation of definitions among others, the qualitative approach provides an enormously useful variety of means for examining how humans make sense out of their worlds.

3.1.2 The Strengths of Qualitative Methods and Data

The strengths of qualitative research derive primarily from its inductive approach, its focus on specific situations or people, and its emphasis on words rather than numbers. Maxwell (1996) and Bogdan & Biklen (1998) outlined five particular research purposes for which qualitative studies were especially suited:

1. Understanding the meaning, for participants in the study, of the events, situations, and actions with which they were involved, and of the accounts that they gave of their lives and experiences. Meaning here included cognition, affect, and intentions.
2. Understanding the particular context within which the participants acted, and the influence this context had on their actions.
3. Identifying unanticipated phenomena and influences, and generating new theories which are well-grounded in the research data. Qualitative research had long been used by survey and experimental researchers, who often conducted exploratory qualitative studies to help them design their questionnaires and identify variables for experimental investigation.
4. Understanding the process by which events and actions took place.
5. Developing causal explanations, and explaining causal process by which some events influenced others. This view of causality was called process theory, and it was different from variance theory which was typically used in quantitative research. The traditional view that qualitative research could not identify causal relationships was disputed by many qualitative researchers (Britan, 1978; Sayer, 1992; Robson, 1993).

In discussing the strengths of qualitative data, Miles and Huberman (1994) started by mentioning the fact that qualitative data would be collected from ordinary events in natural settings, and therefore we would have a strong handle on what "real life" was like. Then, they mentioned local groundedness as a source of confidence in the qualitative data. Another feature of qualitative data was their richness and holism, with strong potential for revealing complexity; such data provided "thick descriptions" that were vivid, nested in a real context, and had a ring of truth that had a strong impact on the reader. Qualitative data were typically collected over a sustained period and thus, were powerful in studying any process in a manner beyond snapshots. The inherent flexibility of qualitative studies (data collection times and methods could be varied as a study proceeds) gave further confidence that we have really understood what had been happening. Finally, Miles and Huberman mentioned that qualitative data have often been advocated as the best strategy for developing hypotheses while exploring a new area; for testing hypotheses by seeing whether specific predictions occurred as predicted; and for supplementing, validating, explaining, or reinterpreting quantitative data gathered from the same setting.

3.1.3 Qualitative Research in Physics Education

Qualitative research methods are neither foreign nor new to physics education. Many researchers use qualitative methods to explore the territories of interest and obtain a general view of the issues involved. A researcher frequently starts with interviewing students or administering a qualitative instrument, then based on the findings of this first round of explorations identifies weaknesses in student learning. The identified weaknesses can be examined further to identify which factors correspond to them. The most typically identified factors include the curriculum or instructional materials, the method and environment of instruction, students lacking the needed background to comprehend the material, and students not having sufficient motivation to give up the scientifically unacceptable ideas and learn the new concepts. Based on the identified problem or combination of problems, researchers start looking for appropriate solutions. After a solution is devised, the next logical step is to evaluate the effectiveness of the introduced solution. The evaluation procedure, however, is often done quantitatively, but the number of evaluators leaning toward qualitative and mixed methods is increasing (NSF, 1999). So at the roots of almost every quantitative evaluation is a qualitative probing. The number of qualitative research studies in physics is constantly increasing. Some examples of qualitative research articles include Mestre, 1991; McDermott, 1984; Trowbridge, and McDermott, 1980; Clement, 1982; Posner, Strike, Hewson, and Gertzog, 1982; Johnston, Crawford, and Fletcher, 1998; Arena, and Vicentini, 1995; Shilhad, 1997; Unal and Zollman, 1999; and Niedderer, 1995.

3.1.4 Suitability of Qualitative Methods for This Project

Several factors conspired in making qualitative research methods the appropriate choice for this project. First, the lack of previous research on students' understanding of surface phenomena and the fact that no written research instrument existed on this topic directed me toward the open-ended and qualitative questions. Second, the exploratory nature of this endeavor, as explained in the research purposes and the broadly outlined research questions, was in perfect harmony with the spirit of qualitative methods. Third, the fact that I was interested in the multiple perspectives and explanations which students would bring to the discussion, and I was not going to assign grades and calculate standard deviations made qualitative methods a more attractive choice. And fourth, there was a fundamental difference between asking students the questions on the interview protocol, see Appendix (1), and questions such as those on standard instruments like the Force Concept Inventory, where complete and widely accepted answers already exist. The questions on the interview protocol covered several topics, like adhesion, friction, and spreading of one liquid on another, which were and still are on the cutting edge of surface science research. Although some answers may be considered more acceptable and more in harmony with what is scientifically known than others may, more complete answers to questions on these topics are still in the making.

3.2 The Interview as A Research Tool

Many methods of data collection are available in the qualitative tradition. Examples of qualitative data collection methods include observation, interview, and collecting and analyzing archival material; documents; photographs; and artifacts. For this research project, however, the interview was chosen as the method of data collection.

Interviewing is the technique of gathering data from humans by asking them questions and getting them to react verbally (Potter, 1996). Interviews can be characterized in several ways. For example, interviews can be structured or unstructured (Krathwohl, 1998); interviews can be casual or in depth (Marshall and Roseman, 1989); and interviews can be ethnographic (Wolcott, 1982), or life history interview (Denzin,1970).

Based on the level of structure involved in an interview, a wide spectrum of interviews existed and some choices had to be made. Krathwohl (1998) provided a table showing the continuum of interviews with increasing amount of structure. Table 3.1 is a reproduction of Krathwohl's table and is provided here for completeness of the description. The characteristics of the interviews used in this research project were those of the semi-structured interview, but the responses were audio taped.

Table 3.1

Continuum of Interviews with Increasing Amounts of Structure

Unstructured	Partially Structured	Semi-structured	Structured	Totally Structured
Exploratory, only area of interest is chosen, interviewer "follows her nose" in formulating and ordering questions. Impromptu conversations that occur during observations are of this nature.	Area is chosen and questions are formulated but order is up to interviewer. Interviewer may add questions or modify them as deemed appropriate. Questions are open-ended, and responses are recorded nearly verbatim, nearly taped.	Questions and order of presentations are determined. Questions have open-ends; interviewer records the essence of each response.	Questions, and order are predetermined, and responses are coded by the interviewer as they are given.	Questions, order, and coding are predetermined, and the respondent is presented with alternatives for each question so that phrasing of responses is structured. Questions are self-coding in that each choice is pre-assigned a code

Many physics education researchers have interviewed students to probe understanding, affect, and motivation. Redish & Steinberg (1999) emphasized the need to listen to find out how students think about physics concepts, and they recommended interviewing as a tool. They wrote: "... we need to listen to the students and find ways to learn what they are thinking." They also wrote: "In trying to find out what students' real difficulties are, physics education researchers use a variety of tools...One way is to carefully interview a number of students, letting them describe what they think about a particular situation....The researcher encourages the students to 'think aloud' and to explain their reasoning. The goal isn't to help the students come up with the 'correct' answer, but rather to understand their thinking." Many other physics education researchers have used the interview method to collect data on students' conceptual understanding.

In this research project, the semi-structured interview approach was used because it made the most appropriate match with the research purposes, research questions, and fitted well with the conceptual framework of the study. The research questions were exploratory. The students' understanding of surface phenomena was an uncharted territory. How students made sense of surface phenomena based on their previous knowledge and experiences, in their own words; and how they reasoned and extrapolated between domains, needed to be probed via a set of open-ended questions. These factors made the semi-structured interview the most appropriate tool.

3.3 The Interview Protocol and Its Development

Since the decision was made to utilize a semi-structured interview and to enter the field (in the sense of qualitative methods) with a prepared set of questions, the development of a set of questions ensued. Throughout this dissertation, the set of questions used during the interviews to elicit students' responses will be referred to as the interview protocol.

The questions in my interview protocol had several characteristics. First, the questions covered a wide range of surface phenomena. According to Adamson (1990), the possible interfaces could be summarized in a formal way in the three states of matter-solid, liquid, and gas as follows:

Gas – Liquid

Gas – Solid

Liquid – Liquid

Liquid – Solid

Solid – Solid

A sixth interface could be that of solid and vacuum. However, since any obtainable vacuum could be represented as a very dilute gas, this interface was represented by the Gas – Solid interface. Although no set of questions to be administered within a finite amount of time in an interview setting could have completely covered a large field of interdisciplinary knowledge like surface science, the questions in the interview protocol touched upon each of the mentioned interfaces.

The second characteristic of the interview protocol was that questions utilized a Piagiatian clinical interview style (Stewart, 1980). In each of the first five groups of questions, the discussion was initiated with the participants being asked a question about some concrete phenomenon; in the sixth and seventh groups of questions the participants were asked to imagine some scenarios of events. In questions one through five, the participants were asked to manipulate some simple set-up, then describe what they observed, and then make an explanation. The description was simply a factual narrative of what was happening, at a very low level of abstraction. This component was included for two purposes. First, it got the participants in the mode to talk about the phenomena; and second, it provided a lowest common denominator to function as a launching point into the discussion. No specific background or sequence of courses was assumed or needed. Beyond the description questions, the participants were asked to make a prediction and to justify it before carrying out any procedures. After making an initial explanation, the questions, within each group of questions, directed the participants to explain the discussed phenomena at a microscopic level. Finally, each set of questions ended with a question asking the participants to reflect on their sources of knowledge for the answers that they provided.

A third characteristic of the interview protocol was the flexibility it provided. Although all participants were asked all of the questions on the protocol, there was sufficient flexibility to ask a participant, "what did you mean by saying...?", particularly when a participant introduced a scientific term that was not used in the question or the previous questions. This kind of further probing was also consistent with the Piagetian clinical interview style.

A fourth characteristic of the questions was their open-endedness. No prescribed answers were given for the participants to choose from. A shift from one question or set of questions occurred when the participant had nothing more to say about the question. No pre-set time limits were established for the interviews, and they varied in duration from thirty minutes to eighty minutes.

A fifth characteristic was that the questions were not unrelated. Some amount of redundancy was involved. For example, the questions asking the participants to provide microscopic explanations, and to explain their sources of knowledge were repeated several times. Additionally, there was a pattern of moving from description of concrete phenomena to phenomenological explanation to microscopic explanation to discussion of the sources of knowledge.

The development of the interview protocol was an iterative and an interactive process. I assembled a large group of questions. Upon the recommendation of Professor Zollman, the number of questions was reduced. Then I added the hands-on activities and broke the questions into sub-questions. After some revisions, I piloted the protocol. Based on the answers and feedback of the pilot participants, further modifications and refinements were made to eliminate ambiguities. Finally, based on the feedback I received after presenting a progress report to the supervisory committee and the Physics Education Research Group, I decided to add a question about atoms and molecules. The question about atoms and molecules did not have a standard place within the protocol, but it was asked when the participants mentioned the words "atom" and/or "molecules".

3.4 The Project Design

> "Contrary to what you may have heard, qualitative research designs do exist" (Miles and Huberman, 1994).

The design in this project could be characterized as qualitative, exploratory, based on a Piagetian semi-structured clinical piloted interview, focused on obtaining a longitudinal view of the intended sample (without having to trace a group or subgroup through four years of undergraduate study), flexible, but guided by broadly articulated research purposes and questions. The design was in accordance with Maxwell's model, in which the research design should have five components: purposes, conceptual context, research questions, methods, and valid findings (Maxwell, 1996). These components were not different from what other researchers discussed (LeCompte and Priessle, 1993; Miles and Huberman, 1994; Robson, 1993). Also, according to Maxwell's model, all of the elements in a qualitative research project should be flexibly connected together and in a non-linear shape, and they should iteratively and interactively guide each other.

3.5 The Pilot Study

To make sure that the questions were understandable, and to revise the interview protocol, I conducted a pilot study. The eight participants of the pilot study were graduate students and postdoctoral fellows in the Physics department. Two of the participants were members of the Physics Education Research Group and two were guests of the group. Additionally, two participants were in High Energy Physics, and two were in Condensed Matter Physics. This variety contributed multiple perspectives and assisted in making some clarifications of the interview protocol. Each of the participants in the pilot study signed an Informed Consent Document, a copy of which was placed in Appendix (2), agreeing to being interviewed and recorded. Participants in the pilot study were not compensated for their participation. I invited each of them personally, and all were colleagues and friends of mine. (They still are.) This sense of familiarity eliminated the need to worry about establishing rapport with the participants, and created an atmosphere of collegiality to exchange ideas and feedback.

The pilot study was beneficial beyond just making refinement of the interview protocol. It assisted in improving my interviewing abilities in this particular context by providing some practice. A list of tips for a "Good Interview" based partially on lessons learned from this pilot study is in Appendix (3). Because all the pilot interviews ran over forty minutes, I decided to use ninety-minute tapes to eliminate the distraction of replacing tapes. I also decided to use a very small recorder, to reduce the distraction that could be created by having a tape recorder in front of the participants.

Since the participants in the pilot study were physics graduate students and postdoctoral fellows, with some actually being involved in surface science research, an upper limit on the expected knowledge was established. Additionally, the critique and feedback of these participants, provided a sense of confidence in the protocol similar to that often referred to as content validation due to examination by a panel of experts when discussing quantitative research instruments.

3.6 The Sampling and the Sample

The sampling in this project could be categorized as purposeful sampling in the sense of Patton (1990), or what LeCompte and Priessle (1993) call criterion-based selection. In purposeful sampling particular settings, persons, or events are selected deliberately to provide important information that cannot be obtained as well from other choices. Maxwell (1996) outlined several goals for using purposeful sampling. For this research study, however, the goal of using purposeful sampling was to adequately capture the heterogeneity in the population and to ensure that the conclusions adequately represented the entire range of variation. Some qualitative researchers (Guba and Lincoln, 1989; Miles and Huberman, 1994) referred to this approach as maximum variation sampling. The goal was achieved by defining the dimensions of variations in the population that were relevant to the study (as discussed in Chapter Two of this dissertation and specified by the research questions), then systematically selecting subgroups to be invited to volunteer to participate in the study. This process resembled that used for stratified random sampling in some quantitative studies.

Recruiting volunteers to participate in the study took some time and effort. First, I visited the Undergraduate Physics Club during one of their meetings and addressed the members present. Most of them scheduled appointments and were interviewed. At that stage, I also invited some of the students taking Engineering Physics 1 to participate and a few did. Then, I decided to interview as many of the physics undergraduate students as possible to form the desired longitudinal view and strengthen whatever conclusions were obtained from interviewing the members of the Undergraduate Physics Club (some of whom turned out not to be physics majors). So, I obtained the official list of all students majoring in physics. All of the students on that list were invited via e-mail to participate. Several students responded to the e-mail invitations, scheduled appointments and were interviewed. Then, I visited the physics classes for physics majors and more participants volunteered. After all of these interviews with physics majors, I felt a need to establish a base–line by inviting some students who were taking some of the most introductory and least mathematically demanding physics classes in the Physics Department. I visited some of these classes, and interviewed several volunteers. There were forty-four participants beyond the pilot study. All participants in the interviews were uncompensated volunteers. No extra credit of any kind was promised nor given.

3.7 Data Collection

After inviting to volunteers and scheduling appointments, I interviewed each of the participants individually. The data collection instrument was the Piagetian style clinical interview with a prepared and piloted protocol. All interviews were audio taped using a small size recorder with ninety-minute mini-cassettes. The choice of recorder and cassette size was based on the pilot study. Audio taping was chosen because it provided a more complete account of what was said during the interviews than note-taking, yet it was less intrusive than video-taping. Of course, some of the participants communicated a few ideas via hand movements, and occasional puzzled looks on their faces, but that was a trade-off because the presence of a video camera could have inhibited some of the participants from expressing themselves freely. Interviews were scattered non-uniformly during the period between November 16, 1998 and March 8, 1999.

3.8 Data Analysis

Introduction:

Several methods of analysis are available to qualitative researchers. These methods can be used separately, but more likely they are used in combinations to fulfill a particular purpose and to balance the weakness of one method by the strength of another. Potter (1996) outlined twenty analytical methods often used by qualitative researchers and grouped them into four categories: orienting methods, deductive methods of construction, inductive methods of construction, and other methods of construction. In this jungle of methods, one should establish a theoretical framework and base the analysis on it. After all, as Potter eloquently stated: "methods are tools. And they acquire their value according to how useful they are in helping the researcher move from evidence to conclusions."

3.8.1 The Theoretical Framework of the Data Analysis

Miles and Huberman (1994) described three broad approaches to qualitative data analysis: interpretivism, social anthropology; and collaborative social research. Although interpretivism seemed to be the most closely aligned to the spirit of this research project, some elements of the social anthropology approach will be adopted in the data analysis According to interpretivism human activity was seen as a "text"- as a collection of symbols expressing layers of meaning. But how would one interpret such a text? Phenomenologists said that the way was through "deep understanding," an empathy or indwelling with the subject of one's inquiries. For the social interactionists, interpretation came via the understanding of group actions and interactions. For both groups, this was an inevitable "interpretation" of meanings made by the social actors and by the researcher. Interpretivists of all types also insisted that researchers were no more "detached" from their objects of study than were their informants (or what I called the participants). One of the hallmarks of this approach to data analysis was the closeness to the original data that the researcher would keep while interpreting the content and trying to capture the essence of an account. The elements that I borrowed from the genre of social anthropology included codifying the research questions and data, and using systematic devices for data analysis. The combination of these two genres seemed to create a stronger approach for data analysis and interpretation.

3.8. 3 Detailed Procedures of Data Analysis

Although the research questions provided some guidance and assisted in analyzing the data, the door remained open for themes and codes to emerge from the data, and hence, kept conclusions grounded in the data.

The Three Stages of Data Analysis

- **First, pre-data collection.**

The data analysis started with the design decisions. I saw design decisions as analytic -- a sort of anticipatory data reduction-- because they constrained later analysis by ruling out certain variables and relationships and attending to others. Some of the design decisions were mainly conceptual: the conceptual framework and research questions, sampling, case definition, instrumentation, and the nature of the data to be collected. Others were related to how data was going to be stored, managed, and processed.

- **Second, during data collection**

Kvale (1988) pointed out that during the interview itself a considerable amount of interpretation occurs. This interpretation was part of what Bogdan and Biklin (1998) referred to as "analysis in the field." I took advantage of the nature of the interview that allowed for follow – up questions as needed, and therefore I constantly evaluated and processed what the participants were saying. However, since I noticed during the pilot study that taking notes while the participant was talking had a distracting effect, I refrained from writing during the interviews. After each interview I wrote a few notes and reflections to capture the highlights and the peculiarities of what stood out during the interview. These notes were not meant as summaries of the interview itself, but were very helpful in generating reflections to assist in the future contacts. These brief notes were also instrumental in deciding whether to interview more students from a particular class or move to a different group of students. Additionally, these notes assisted in creating the first list of potential codes and themes to look for.

- **Third, post data collection**

Despite the fact that I had some preliminary thoughts about data reduction, coding, themes and other analysis related activities before completing the data collection phase, the bulk of the analysis took place after the data collection was completed. The following steps were written to highlight the main steps performed during data analysis.

1. I carefully listened to each of the tapes and took extensive notes about the content and my reflections of the content. I also built a matrix using the counter on the recorder to assist in locating each of the questions for each of the participants. This table served as a punctuation and reference method in the rest of the analysis.

2. Based on these notes, I generated an initial list of codes.
3. I listened to the tapes again, revised and refined the list of codes to make it more inclusive, better structured and streamlined. At the same time I identified the occurrences of each item on the coding list. I marked the occurrences of relevant code information using counter on the recorder.
4. I coded several interviews again. The purpose was to establish intra-coder reliability. Miles and Huberman (1994) provided an operational definition for (code-re-code) or intra-coder reliability as:

   Reliability = (number of agreements)/(number of agreements + disagreements)

   I modified and added codes, then I repeated the coding until a reliability of 98% was reached.

5. I also carried out a procedure to insure inter-coder reliability. First, I invited a graduate student and a postdoctoral fellow to form a first panel, in addition to myself. Each member of this panel had previous experience completing a research project where qualitative data analysis was used. The first panel independently coded three tapes selected randomly. Each member of the first panel coded each of the tapes. Then consensus was reached about the suitability of the code-set. Then, I formed a second panel. The second panel consisted of a postdoctoral fellow, a graduate student, and an undergraduate guest, in addition to myself. A different set of three tapes was randomly selected and used by the second panel. After I explained the coding procedure and the code-set to each member of the second panel, each independently coded each of the tapes. Upon comparison of

agreements and disagreements, I found that I had an average of 87% agreement. Then I moved to the next step of analysis.

6. After the initial coding, I organized pattern codes. Pattern codes were explanatory or inferential codes that identified emergent themes, configurations, or explanations. They pulled together a lot of material into more meaningful and parsimonious units of analysis. Miles and Huberman (1994) referred to pattern coding as a sort of meta-coding. The importance of forming pattern codes could be learned from Kaplan's (1994) statement: "the bedrock of inquiry is the researcher's quest for repeatable regularities."
7. I examined the repeating patterns for the themes they carried.
8. Then, I combined the themes in a collective interpretive analysis of the themes.
9. I wrote the findings in a narrative qualitative style where the data and the various layers intertwined.

3.8.4 Instrumentation Decisions

Instrumentation is the general heading which qualitative researchers (Miles and Huberman, 1994) use to refer to the general issues of technical choices such as note-taking and its details of when and how, recording; transcriptions; and similar issues.

- **Were They Subjects or Something Else?**

I adopted the recommendation of American Psychological Association's Publication Manual and use the term *participants* in place of *subjects* throughout the study. The term *participant* implied a more active, and voluntary role in the research. All participants were promised confidentiality, therefore I did not use their names.

Instead, I referred to student participants using SP1, SP2,..., SP44 to, and I referred to participants in the pilot using PP1, PP2,..., PP8. The numbers indicated the chronological order of the interview. For example, SP24 meant the twenty-three student participants were interviewed before this particular student.

- **Should I Compensate the Participants?**

I considered compensating the participants either monetarily or via some extra credit. The motivations for this consideration existed. First, having some reward, financial or otherwise, would entice a variety of students to participate. This variety would reduce the bias that could result from the participants being volunteers. The second motivation was to increase the number of participants. After considering the situation, however, I decided against offering any tangible rewards. Offering any compensation would have replaced one sort of bias for another. Volunteers were self-motivated and took the task seriously. I was concerned that compensated participants would be only motivated by whatever reward was being offered and take the task less seriously.

- **Building Rapport with Participants:**

Building rapport with the participants was facilitated by several factors. First, when I invited the students to participate, I explained the purposes of the interviews and what to expect during the interviews. Second, at the time of the interview, I started by providing a brief introduction and description of the interview and its purposes. Third, being promised confidentiality and no grading seemed to put students at ease to express their thoughts. Fourth, I built on my many years of teaching and dealing with students and tried a non-intimidating, non-judgmental tone that facilitated establishing rapport and putting the participants at ease.

- **To Transcribe or Not to Transcribe?**

While most of the texts on qualitative analysis assumed that interviews would be transcribed, and the data analysis would follow from the transcripts, I choose not to transcribe the interviews. The motivations for not transcribing were to stay close to the original data (on tapes), and to possibly analyze items that could not be analyzed by using transcripts. Examples of the second point were the duration between being asked a question and declaring "I do not know", or the participant sounding upbeat and excited about discussing the questions or not showing excitement. As a consequence of not transcribing, I did not use any of the specialized software programs of qualitative data analysis since most of these programs needed written documents to analyze.

- **Should I Use First Person Pronouns or Passive Voice?**

I realize that traditional formal research reports used passive voice. However, in keeping faithful to the spirit of qualitative methods, I chose to use the first person pronoun "I". Many authors of qualitative research methods warned against attempting to detach the author from the content and details of the actions taken in the research project. Miles and Huberman (1994) captured the essence of what style and what voice to use by saying:

> Matters of style are connected with the choice of voice... Using passive instead of active verbs, 'objective' stances rather than honestly personal ones, and indirect locutions instead of straightforward talk have a long and dishonorable history in traditional reporting. They serve only to wrap the

writer in the mantle of 'science," while mystifying and alienating the reader.

Since I did not want to mystify and alienate the readers, nor be part of what Miles and Huberman referred to as "dishonorable history in traditional reporting", I choose the active narrative voice in writing this dissertation.

3.9 Possible Limitations

No research study was ever done without some limitations. A possible limitation in this project would be related to the site of the study. This project was carried out at one site, Kansas State University, a large mid-western public university with open admissions. The fact that it was one special site possibly imposed some limits on transferability of the findings. The students taking introductory physics classes at other institutions may have better or worse preparation when they join the university.

A second possible limitation was due to the fact that audio - taping rather than video - taping was used. Many participants used hand movements in their explanations. These hand movements could be considered lost data. However, the intrusiveness of a video camera could have prohibited some students from expressing themselves freely.

A third possible limitation was the fact that only one method of data collection was used. Lack of previous efforts in the topic of this research project made it impossible to find another instrument or approach to triangulate the data.

A fourth possible limitation was the fact that cassettes were not transcribed in the usual verbatim sense often talked about in some qualitative method textbooks. In this study, verbatim transcription was not viewed as the best possible way to go. In fact, it would have distanced me from the data, created a huge volume of printouts, and placed some limitations on what was to be analyzed like the duration of pause of the participants before answering or declaring “I don’t know”.

Although careful measures to insure both intra-coder and inter-coder reliability were undertaken, a possible fifth limitation was having only one person coding and analyzing the data.

As the title of this section indicated, and I intended to emphasize, these were "possible" limitations. Whether one would consider them as limitations could be subject to debate.

3.10 Reflections on the Process

I used qualitative methods in this project to gain an understanding of several aspects of students’ reasoning and concepts of surface phenomena. The steps were not always linear, and each decision affected many others. While conducting the interviews, I felt that both the interview protocol and I were combined into one dynamic research instrument. The participants provided me with a great amount of data that took a considerable amount of effort to analyze, and to distill the findings into a presentable form. Overall, however, the process was an enjoyable challenge.

CHAPTER FOUR

DATA AND ANALYSES

4.1 Introduction

Forty-four tapes of interviews carried a large amount of rich qualitative data. Presenting such a magnitude of data in its raw form would not be illuminating. Instead, I put the data through various stages of organizing, filtering, reducing (in the qualitative sense), and interpreting. A beautiful analogy describing the process of qualitative data analysis was provided by Krathwohl (1998). Krathwohl started the chapter on Qualitative Data Analysis by quoting Pablo Picasso's definition of art: "Art is the elimination of the unnecessary." Then, he drew a parallel between art and qualitative data analysis. Krathwohl (1998) wrote:

> You probably have never thought of art as the 'elimination of the unnecessary' as suggested by Picasso, but this is what the sculpturer does in revealing the form hidden within the stone. It is what the painter does in selecting which are the elements in a composition and arranging them creatively. The musician as well, finds a melody and suitable embellishments among a host of possibilities. Doing good research is also part art, and – as Piccaso's epigram suggests – part of the art of qualitative research is cutting away those notes and details that are not of consequence in order to concentrate on what is important – data reduction.

I used three layers of data analysis. The first layer was a phenomemographical approach, as explained by Marton (1986). This step included an elaborate coding of what each student answered to each of the questions. The interview protocol served as an organizer in establishing what Miles and Huberman (1994) referred to as the cross-case mega-matrix. The list of codes went through both intra–coder and inter–coder reliability checks. The cross-case mega-matrix served as an organizing tool, a theme locator, and an analysis audit trail. In section 4.2 I present the phenomenographical categories of answers on a question-by-question basis.

The second layer of analysis was a thematic approach. After examining the cross – case mega-matrix and the phenomenographical categories, reviewing the field notes, examining the reflections and summaries, and repeatedly listening to the tapes, a set of themes emerged. Bogdan and Biklin (1998) defined a theme as "some concept or theory that emerges from your data: some signal a trend, some master conception, or key distinction." The importance of going beyond categorizing the data to the level of themes was stressed by Glaser and Strauss (1967) who stated that, "Academic researchers interested in generating theory see the development of 'generic themes' as the most laudable goal for researchers." Many themes emerged, but the themes which received my attention and focus were those that had direct relevance to this project's purposes and questions. In section 4.3 I summarize and elaborate on the emerging themes.

The third layer of analysis aimed at bringing the themes together at level higher than individual themes. I was interested in connecting the emerging themes to theories and conceptual frameworks. To accomplish this level of understanding, I carried out an interpretive analysis of the emerging themes. Section 4.4 captures the essence of the interpretive efforts.

4.2 Phenomenographical Analysis and Presentation of Data

According to Marton (1986), phenomenography is a research approach designed to answer certain questions about thinking and learning. It originally was developed by a research group in the Department of Education, University of Gothenburg, Sweden. The word "phenomenography" was coined in 1979 and appeared in print for the first time two years later. When investigating people's understanding of various phenomena, concepts, and principles, phenomenographers repeatedly found that each phenomenon, concept, or principle could be understood in a limited number of qualitatively different ways. Phenomenography is not concerned solely with the phenomena that are experienced and thought about, or with the human beings who are experiencing or thinking about the phenomena. Nor is phenomenography concerned with perception and thought as abstract phenomena, wholly separate from the subject matter of thought and perception. Phenomenography is concerned with the relations that exist between human beings and the world around them. Phenomenographers do not make statements about the world as such, but about people's conceptions of the world. Also, according to Marton (1986), phenomenographers categorize their "subjects'" descriptions, and these categorizations are the primary outcomes of phenomenographic research.

The first layer of analysis I followed was a phenomenographic approach. The categories that emerged were as follows:

4.2.1 Question 1: Oil on Water

In this question I asked each student participant to take a drop of oil and to put it on the water in a transparent container. Then, I asked the participants to describe what they observed. Students' descriptions fitted into three categories. The first category was a dynamic image of what the oil drop was doing, and what was happening. Words and phrases like: "the oil drop is spreading"; "the oil drop is thinning out"; and "the oil is forming a thin layer" exemplified the dynamic image category. The second category of answers was a static image of what happened. Examples of this category were: "a thin layer"; "a film"; and "a smooth film". The third category of descriptions did not describe the oil drop directly, but focused on the observed patterns of light like "interference"; "diffraction"; and "rainbow of colors". These categories were not mutually exclusive. Thirty-seven students' answers included elements from more than one category.

The explanations provided by students for why the oil droplet spread on the surface of the water could be classified into:

1. Surface tension (11). Seven students focused on the strength of the surface tension of the water, while four focused on the weakness of the surface tension of the oil droplet.
2. Gravitational force (10). The effect of gravitational force was exemplified by statements like "gravity makes oil spread," and "the oil droplet is trying to relieve itself of the gravitational potential energy." SP3 imagined the oil molecules as a pile of marbles spreading on a solid surface.

3. Oil has lower density so it stayed on the top (14). This argument was introduced mostly by the students in The Physical World class, and it was not as emphasized by the more advanced students.
4. Oil and water do not mix (18). In this case the focus was on some of the oil's or water's molecular attributes, or both. The justification for why oil and water do not mix varied in sophistication and details. Three students said that, "water molecules are repelling the oil molecules" others talked about "polarity", and the fact that "water is polar and oil is non-polar". Those with several chemistry classes introduced concepts like "oil is hydrophobic".
5. Diffusion (7). Seven students, SP4 for example, considered that there was a large amount of oil in one location, and no oil in the area surrounding that location. Therefore there was a difference in chemical potential, and since the entropy of the system would increase when the oil molecules were farther apart, they would not stay close together even if there was no gravitational force.
6. The "I do not know" and its variations like "I am not sure", "I do not recall" were common among students in the beginners group category (12).

4.2.2 Question 2: Soap on a Penny

Forty-two students predicted that the dry penny would be able to hold more water on its surface than the penny with a thin film of soap would. Seven students predicted the outcome to favor the penny with soap and five of whom changed their answers and selected the dry penny. The initial justifications for predicting that the dry penny would be able hold more water on its surface focused on:

1. Soap weakened the surface tension.
2. Soap made water slide.
3. Soap took the available volume.
4. Water is polar and soap is non-polar, so there would be repulsion.
5. It is just a guess!

The students who predicted that the penny with soap will be able to have more water on its surface explained their reasoning:

1. The presence of soap strengthened the surface tension.
2. Water would slide easily from the surface of a metal, but soap would prevent it from sliding.
3. On the surface of the dry penny, there was nothing for water to hold on to, but the presence of soap would provide something for the water to interact with and create foam.

Carrying out the procedure of using the dropper and putting water on both surfaces was a confidence builder when the output of the experiment matched the initial prediction. Also, observing the water bead up on the dry penny and "run" on the penny with soap seemed to provide more hints to the students who stated that they were "clueless" as to what would happen.

After the students carried out the procedure, I asked each participant to explain on the microscopic level the differences between what took place on the two pennies. The observations seemed rather helpful for many students and assisted them in creating more detailed explanations than before. Thirty-four students focused their explanations on surface tension arguments after the procedure than did before (20). However, not all of the students who focused on surface tension called it by that name. Three students used the name "surface cohesion", and one student called it "the contractive forces of the water." Also, when the students talked about surface tension, ten students associated the word surface with the interface between the penny and water or between the film of soap and the water. Five students said it was the surface on the top of the dome of water because oil molecules placed themselves between water molecules and weakened the bonds. A third group of students, like SP20, changed their minds about which interface they meant. SP20 stated before carrying out the procedure that, "soap breaks up surface tension of the water." She also made a drawing to show that she meant the flat interface between the soap and the water. After carrying out the procedure she said, "Hmmm! Now that I looked at what was happening, I wonder if the surface tension up here (pointing to the top of the water dome in a graph she drew) is not affected too. From what I saw, when water hits soap, you get soapy water, not a layer of soap and a layer of water as in the case of oil and water."

When the experimental result did not match the initial prediction, as in the cases of SP14 and SP16, students immediately suspected whatever definitions and explanations that they provided initially, or that became confused as SP24 did. No student doubted the experimental technique s/he was using, even when there was some procedural error. Despite being instructed to repeat the procedure exactly the same for both pennies, SP16, for example, dropped the water on the dry penny from a noticeably higher elevation than he did on the penny with soap. I hoped that he would mention this difference in elevation as part of justifying a possible discrepancy with the prediction, but he did not. SP24 put almost all of the drops very close to the edge on the dry penny, leaving most of the penny empty. When he repeated the procedure, however, he put the drops in the middle causing more water to accumulate on the penny with soap. Additionally, when the experimental result did not match the original prediction, students became more reluctant to speak, sounded less confident, and lowered their voices until we moved to the next question.

The ratio of the number of drops on the penny with soap (when water spills out) to the number of drops on the dry penny (when water spills out) was between 0.4 and 0.6 for most of the participants. This ratio is interesting because it could be used for building an instructional activity where students learn about contact angle between a liquid and a solid without going through lengthy mathematical derivations.

4.2.3 Question 3: Scotch Tape

Responding to the initial question "Why does the Scotch tape stick?" the most common response was "It is sticky" or "It has some glue or adhesive." Four participants replied by saying: "It is Scotch tape, it is supposed to stick." Nine students mentioned "friction" or "attractive forces."

Further probing into the attraction mechanism and what the participant would see if s/he observed the sticking process under a very powerful microscope proved rather productive. The categories of the students' answers could be categorized as:

1. There is some semi-liquid material on the tape that seeps into the crevices of whatever surface the tape is being adhered to (21). Four students visualized that this material would expand to maximize contact area after it seeps into the irregularities of these surfaces. SP15 imagined the sticking process as a tree with roots. These roots would hold the tape to the surface. SP19 imagined

that, "whatever surface the Scotch tape is being stuck to acts like some suction mechanism to draw the sticky material inwards."

2. A chemical bonding between the glue and the surface makes the tape stick to the surface (16).
3. Electrostatics, where polarization of the glue molecules causes inducement of charge on whatever surface the tape is being adhered to (14).
4. The molecules of the glue are very long and they have an ability to hold hands with the molecules of the plastic tape on one end and to the molecules of the surface on the other end (11).
5. It is some kind of friction. Four students said, "It is friction," then elaborated on their answers. For example, SP20 explained the attraction mechanism by saying, "I'd say that maybe on the molecular level the top layer of each surface kind of meshes with the other one." When I asked her, "What would you see under a very powerful microscope?" she said, "I would expect that the surface of the tape is kind of rough. No, maybe it will be just kind of rough, but maybe it will have some kind of projections, like hooks. Maybe it will be like Velcro. It may have something that projects a lot and gets between the molecules of the other surface, kind of interweaves between the molecules."

Five students explicitly stated that the attraction mechanism of Scotch tape had no relation to electrostatics. SP7 (a physics senior) replied to my question regarding the attraction mechanism of the Scotch tape by saying: "I do not think it is electric attraction or anything like that. I think it is purely the physical properties of the sticky stuff."

4.2.4 Question 4: Painting

Describing and comparing what happened after the participant wrote a letter with a brush that was dipped in paint and then wrote the same letter (at a different spot, of course) with a second brush that was dipped in water, several categories emerged from the students' answers:

1. Twenty-one students focused most of their comparisons on visually "obvious" cues. Examples were: "Water is transparent, but paint has color", and "The paint is red, but I can hardly see the water."
2. Some answers related more directly to the interaction between the paint or water and the metallic shelf. Examples of this category were: "Water did not stick, but paint stayed in place" (28), and "Water beaded up, while paint is sort of smooth" (23).
3. A third category of answers discussed attributes of paint and of the water that went beyond description to explanation. An example of this category was: "Paint probably has some adhesive in it." (7)

When the students tried to explain the differences in the behavior, thirty-five participants did not invoke microscopic arguments until they were explicitly asked to do so. The initial explanations of differences focused on:

1. Surface tension. Twenty-seven of the participants stated that water had stronger surface tension than did paint, and then used the surface tension idea to explain why water beaded up and paint did not. Eight students, however, stated that the paint had a stronger surface tension than that of the water and

then used this idea to explain why paint stuck to the surface better than water did. During the discussion several participants shifted from saying that paint had stronger surface tension to saying that water had stronger surface tension.

2. Several students indicated that the paint was thicker (17), denser (3), more viscous (7), and had more texture than the water (2).
3. Twenty-three students indicated that "the chemical composition of paint," or "paint had something in it to make it stick," and used idea as basis for their explanations.

When the discussion shifted to the microscopic level, twenty-two students just repeated what they said in their previous explanation. In addition to the mentioned categories, the following categories emerged:

1. Water has hydrogen bonds, and paint does not.
2. Water has hydrogen bonds, and the shelf does not.
3. Paint molecules are polar.
4. Paint molecules form long chains and form bonds with the shelf.
5. Electrostatic forces favor paint over water and make paint stick.
6. "I have no idea", "I do not know" and similar statements.

4.2.5 Question 5: Writing with Various Media on Various Materials

When I asked the participants to use a pencil to write on the paper and to explain the mechanism for the pencil to leave a mark on the paper, thirty-six participant started by mentioning that the lead of the pencil was made of graphite which was a soft material and could easily leave a mark. Then, as the discussion developed, however, several categories of answers emerged.

1. The composition of the lead of the pencil. Fourteen students described the lead as made of sheets that could easily slide; twenty-two described the graphite molecules as loosely bound together.
2. The composition of the paper. The participants' discussion of the surface of the paper included saying: "The paper is rough" (25), "The paper has microscopic ridges" (5), "Paper has stronger molecular structure than graphite" (3) and "Paper molecules stick up and take some graphite." (1)
3. Friction. Ten participants indicated that friction was responsible for the mark being left on the paper but could not elaborate.

When the students explained the differences between the "clear mark" left by the pencil on the paper, and the "faded mark" or "just an indentation" which the pencil left on the transparency and the shiny piece of plastic, more of the students elaborated on the structures of the surfaces than after writing with a pencil on paper than did before. Students suggested that "The paper was rougher than these surfaces", "The surfaces of the transparency and the shiny piece of paper were slicker or smoother". Then, in discussing the phenomenon microscopically students hypothesized or inferred that "The molecules of the transparency and the shiny piece of paper were smaller than those of the paper", "The molecules on the transparency and the shiny piece of paper were more tightly bound than in the case of the paper", "The transparency and the shiny piece of paper did not have holes while the paper did", and "There was less electrostatic attraction between the graphite and the surfaces of the transparency or the shiny piece of paper than between the graphite and the regular paper." SP33 went against the trend when she thought that the pencil did not leave a clear mark on the transparency and the shiny papers because the latter ones had too much friction for the pencil to operate.

As I asked the students to use a fountain pen to write on the three surfaces and then explain what happened, a discussion very similar to the case of the pencil ensued. In this case, however, the idea of absorption took the place of that of friction. To thirty students that was the only difference. The paper absorbed the ink for several reasons like "Paper had cracks", "Paper has pores", "Paper has ridges", "Paper's molecules are not very tightly bound", "Paper was made of wood which absorbed liquids by capillary action, therefore the paper inherited the same ability", "The paper allowed the ink to chemically bond with it", and "Ink is just a liquid with some pigment; when the liquid evaporates, the pigment remains." Using the pen to write on the transparency and the shiny piece of paper seemed to reinforce the microscopic explanations which the students provided in the context of the pencil. They sounded more confident as they repeated statements like "smaller pores on the transparency than on the paper"; and "Transparency molecules are much more compressed than those of the paper."

After the participants used the transparency pen, and indicated that it left a clearer mark on all of the three surfaces, I asked, "Why did the transparency pen leave a clearer mark on the transparency than the fountain pen did?" The answers which the students provided focused on:

1. "The method of delivery" as nine students called it. Two students indicated that the "Tip of the transparency pen acted like a sponge".
2. The medium in which the ink molecules of the transparency pen was different. Eight students said: "The transparency ink is dissolved in alcohol

which evaporates faster than the water which the ink in the fountain pen is dissolved."

3. The ink in the transparency pen either "Had some chemical that made it easier for it to stick to the surface of the transparency" (18), "The molecules of the ink in the transparency pen were very much smaller than the molecules of the ink in the fountain pen, and therefore they could penetrate the tightly bound small molecules of the transparency" (3), "With the transparency pen you do not write, you just paint" (4), "The molecules in the ink in the transparency pen were not polar like those of ink in the fountain pen and therefore were not rejected by the transparency." (3). Also sixteen students said: "Something is different in the pen" and three students said: "The transparency pen was made for it."

4.2.6 Question 6: A Flying Atom Hitting Surfaces

After overcoming the initial surprise of "an atom hitting a surface! You mean an individual atom actually moving around?", as expressed by twenty students, the students focused on the question I asked, and started providing answers which could fit into several categories:

A. For an atom hitting a liquid surface:

The categories that emerged from the students' answers were:

1. Twenty students wanted to know what atom and what surface before providing an analysis. Twelve students assumed, on their own, that liquid meant water.

2. Three students suggested that surface tension would prevent the penetration of the atoms into the liquid.
3. Two students were sure that if an atom reached a liquid surface, then by diffusion action and Brownian motion of the atoms of the liquid itself it would go into the liquid. The atom, however, would slow down as it reached the surface.
4. Thirteen students suggested that an atom would hit and bounce back. There was more than one explanation for why the atom would bounce back:
    a. The atom would have a head-on collision with one of the atoms on the surface.
    b. The electrons of the atom and the electrons of the atoms on the surface would repel each other strongly enough to make the atom bounce back.
5. There was an "it depends" group of answers. The following list of "it depends was compiled from the answers of all students who used the phrase "it depends." No individual student used all of the list:
    a. It depends on what the liquid is.
    b. It depends on what the atom is.
    c. It depends on whether the atom could combine to the surface chemically.
    d. It depends on whether the liquid is attracted to the atom or not.
    e. It depends on whether the atom has a net charge or not.
    f. It depends on whether the surface is charged or not.
    g. It depends on the surface tension of the liquid.
    h. It depends on the atom's velocity.

i. It depends on the atom's energy

j. It depends on the atom's momentum.

k. It depends on the atom's size in comparison with the spaces between the atoms in the liquid.

B. In the discussion of an atom hitting a solid surface, several categories of answers emerged:

1. Eleven students indicated that there should be no fundamental differences between what happens when an atom hits a liquid or a solid. For example, SP3 said, "The solid is a liquid, it is just a little more solid", and SP15 said, "The liquid is a solid, it is just a little more liquid."
2. The atom will definitely hit and bounce because it is hitting a solid with the atoms more closely packed and a higher probability of hitting an atom in a head-on collision (26). It may make a dent in the surface of the solid, however (1).
3. The surface could absorb the energy of the atom but not the atom itself (1).
4. The same list of "it depends" as for the case of the liquid emerged in the students' answers.

C. In answering the question: "If an atom hits a surface, would it have a better chance to stick to a rough surface, or to a smooth surface?" the answers naturally fitted into three categories, in addition to the "I don't know category". Thirty-two students chose the rough surface, and justified their answers by saying: "More surface area", "More configurations on the rough surfaces", "More ridges on the rough surface", "The atom has more than one chance to stick to a rough surface", and "More interactions with the electromagnetic fields of the rough surface." One student chose the smooth surface. Eight students declared that it did not matter because at the molecular level there would be no smooth surfaces. Four students said: "It is hard to tell", and one student believed that the atom would not stick to either surface.

4.2.7 Question 7: A Silver Spoon in an Oven

Although thirty-five students started by saying: "The spoon will get hotter", sixteen stopped to think about the emptiness of the oven. The fact that the oven was totally empty presented a problem to ten students like SP11 and SP12 who said: "If there is no air, heat will not transfer." SP9 asked, "How are you heating the oven? Are you using an electric coil?" I said, "Yes." Then he said: "If there is no air, the spoon will stay at the same temperature. Probably it will lose temperature." The need for air in the oven was expressed by other students, but the probability that the spoon could "lose temperature" was not expressed by anyone else. In this context SP9 could not imagine the spoon's temperature increasing without air, but he could imagine the spoon "losing temperature" without air. Three students went further than wanting air in the oven. SP34, for example, specified that there must be oxygen in the oven for heat to transfer. Only nine students remembered radiation as a way of heat transfer.

Eight students seemed confused due to some formal instruction or definition they learned. SP11 talked about the spoon as a Carnot engine. She said: "As hot air comes into the spoon, it kicks cold air out of the spoon, and that is how the spoon would become hotter." When I asked her about how she came up with her answer, she replied: "We just talked about heat engines last week." As SP20 started describing what happened to the silver spoon, she ignored the issue of emptiness of the oven. But when I asked if there was any difference between what happened to the surface and what happened to the bulk as the spoon was heated, she stopped to think about the lack of air in the oven. Then she said, "The surface becomes hotter first. The energy gets transferred to the surface first because air molecules bounce off the surface first. If the oven is totally empty, and there is no air, hmmm, I am not sure. [pause]. If temperature was a property defined to be proportional to the kinetic energy of the moving molecules, then without air molecules you would not even have temperature! I would have to think about that." A similar argument to that introduced by SP20 was also presented by SP43.

When I asked about what happened at the surface, and how that compared with what happened inside the spoon, four categories of answers emerged. The most common was in terms of the delayed effect, or as thirty-four students stated: "The surface will be hotter because heat must go through the surface first." The second category was: "There should be no difference." (17). The third category was " I do not know", or "I am not sure" (5). One student, SP2, surprised me by saying: "The surface will be cooler than the center since the surface will be is losing its most energetic atoms. Its [the surface's] distribution of kinetic energies is going to have a lower mean kinetic energy than that at the center of the spoon. Therefore the surface will have lower temperature than the inside." None of the students considered the fact that the surface layer may have a different structure from the bulk as a cause of possible variation between the behavior of the surface and that of the bulk.

When I asked the students: "If one could shrink her/himself to a really small size, what would s/he see at the surface of the spoon as the temperature is increased?" I meant to solicit ideas of what the students imagine at the microscopic level. The question was a slight variation from the standard: "Explain what is taking place at the microscopic level." I was impressed by the vividness of the details that some students provided. The answers provided by the students included: "He will see an earthquake type of event with the atoms shaking back and forth." "Atoms start to move faster than before." "Atoms vibrate and get farther apart from each other." "Atoms move faster and farther out about their positions." "As the surface temperature becomes high enough, more and more atoms fly out, almost like water boiling." SP17 imagined himself looking through a camera or some lenses that could be zoomed to show finer and finer details. He said, "From a distance, he sees something like an ocean. As he gets closer the details start to become clearer, and the atoms will look like little spheres with clouds surrounding them. As he becomes closer still he would be able to see these atoms vibrating in some complicated patterns. As the temperature increases, the vibrations increase but I do not know how to quantify this increase mathematically." Eighteen students used the words "atoms" and "molecules" interchangeably as they discussed what happened to the silver spoon. For example, "The molecules start to hit each other more than before because these atoms or molecules in the silver spoon start moving quite fast as the temperature increases." Five students imagined that, "The individual atoms become bigger." SP19 said, "I would say the atoms become bigger. So, they increase the size of the spoon. The radius of the electron cloud could increase, and the size of the nucleus increases slightly." So, not only do atoms move more than they did before, but also the individual atoms swell and grow bigger. Five students indicated that "The increase in temperature would make the electrons rotate faster and faster around the nucleus until they eventually break free from the nucleus." And three students said, "As the temperature increases, the electrons will spin faster."

Then I decided to probe further into the microscopic world of the interviewees by asking: "If our imaginary friend was shrunk to the point where s/he could be embedded within the surface, what would s/he feel as the temperature is increased?" The answers to this question were very similar to the answers obtained by asking the previous question. The words "See atoms (or molecules or electrons) moving faster" were replaced with "Get hit by the fast moving atoms (or molecules or electrons)." In this case, however, the descriptions sounded more dynamic than before, and more students mentioned analogies like earthquakes.

4.2.8 Follow-up Questions:

For purposes of clarity and due to the importance of certain terms and concepts, I added four follow-up questions. Each of these questions was asked after the student introduced the related term in the description or the explanation of some phenomena. For example, if the student said: "Oil spreads out on water due to surface tension", that would give rise to the follow-up question: "What do you mean by surface tension?" Surface tension and friction were mentioned by most of the students. Additionally, because I was interested in how students explained the physical phenomena microscopically, I asked the follow-up questions: "What is a molecule?" and "What is an atom?" Despite the fact that these follow-up questions were asked in the context of the protocol questions, I decided to provide separate analyses of them.

a. What Do You Mean by: "Surface Tension"?

The students' answers to the question: "What do you mean by surface tension?" grouped themselves into the following categories:

1. Surface tension is "a film – like something" (16), "the little skin on top of the water", "the little wall on top of the water." According to this definition, surface tension is a material layer on the surface of the liquid.
2. Surface tension is a force, as in "The attraction of the water to itself." (5).
3. Surface tension is a manifestation of some underlying chemical process. Examples were: "It is how tight the water molecules are tied together due to hydrogen bonding" and "Some chemical bonding that causes the water to bead up." (9).
4. Surface tension is defined as "energy/area." (1).

Some students combined two or more of these definitions. Also, when students said, "the attraction of water to itself," there were three distinct views among students. Some emphasized that "Surface tension is the attraction of water to itself except on the surface" while others emphasized that "the atoms on the surface are more strongly tied together." The third group said, "Surface tension occurs because in the middle there are attractive forces from all directions while on the surface there is [sic] only attractive forces downwards, and nothing is pulling the molecules on the surface upwards."

Another group of students felt that surface tension became "common knowledge", as SP22 called it. SP22 said, "I do not think I can give you a technical definition of surface tension. I have heard this term in almost every science class I took since junior high school. I only associate it with water wanting to cling to itself more than it wants to cling to other materials, but I forgot the technical details and definitions associated with it. Now, I consider surface tension as common knowledge, but I could have given you more technical details in my junior year in high school."

b. What Do You Mean by: "Friction"?

Thirty students used the word friction at least once during the interview. When I probed further into what the students meant when they used the word friction, the following categories emerged:

1. Friction is a force (19), as in "Friction is this force that acts between two objects," and "The attraction that stems from electrostatic attraction of two objects."
2. Friction is a mechanism (11), as in "friction is how the pieces interlock between two solids." And "friction is what happens when two objects slide on top of each other and rub each others electrons off."
3. An image without definition (5), such as "It is like when you have two blocks slide past each other." And "Like moving your hand on a bunch of balls, some are sticking out higher than others."
4. Some statements did not refer to a physical entity or mechanism (3). Examples were, "Friction is a nasty thing", and "Something that can complicate physics problems."

c. Follow-up Question: What Is an Atom?

As the students started attempting to relate the macroscopic phenomena to microscopic explanations, I decided that it would be useful to examine what they meant by the words "atom" and "molecule" in the context of their explanations of surface phenomena. Then I examined the patterns of these definitions. For the "atom", the students' definitions and statements focused on

1. Invisibility (5): "An atom is a small and tiny thing, I have never seen one but I was told that they existed."
2. Building block (19): "The building block of the universe", "The smallest piece of matter", and "The smallest particle with the characteristics of the element."
3. The atom in terms of what it consists of and how the components are arranged (24): "Atoms consist of a positively charged nucleus with electrons orbiting around", "An atom is a nucleus with protons and neutrons and around that you have an electron cloud, like probability density thing", "A positively charged nucleus with electrons orbiting on the outside, but in quantum mechanics the electrons are going to have probabilities of being in several spots or orbitals."

The categories outlined above were consistent with the findings of Unal (1996) who made a cross-age investigation of how students, particularly high school students, described the atom.

d. Follow-up Question: What Is a Molecule?

The explanations provided by students for "What is a molecule?" varied in detail and sophistication of explanation. The categories of answers were classified as:

1. The molecule is a collection of atoms held together (28). This statement or a variation of it like "More than one atom put together" or "a group of two or more atoms combined together in some formation" occurred repeatedly in the

definitions. Eleven students mentioned water as an example of what a molecule was by saying "Molecules are atoms put together like water where you have two hydrogens and an oxygen."

2. The molecule is the smallest particle of matter. This was the definition which seven students also attributed to the atom.
3. In terms of the relation between the molecule and matter, there were two groups of beliefs:
   a. "The molecule contains all the physical properties of the substance." (9). So whatever attributes the substance has like hardness and color, the individual molecules had the same. The fact that some students considered the microscopic world as totally isomorphic to the macroscopic one, except for a scale factor corroborated the findings of Albanese and Vicentini (1995) who interviewed thirty secondary school Italian students while investigating their understanding of the particulate nature of matter.
   b. "The molecule contains the chemical properties of the substance." (7). For example, if the substance is water and made of hydrogen and oxygen, then each individual molecule is also made of hydrogen and oxygen.
4. SP13 introduced an interesting twist to what everyone else was saying when she decidedly said: "Molecules are a representation of what we believe." When I asked for clarification she said: "Molecules are not balls on sticks like we see in chemistry textbooks, all representations of molecules are only representations of what we choose the molecules' reality to mean to us."

5. Of course there was the “I do not remember” group. However, two students remembered that there was a relation between the atoms and the molecules but were not sure. One student said, “I am not sure if atoms were made of molecules or molecules were made of atoms. I learned that in chemistry a long time ago. I think it was last year.”

4.2.9 Sources of Knowledge

The sources of knowledge which students cited in answering the questions were easily divided into formal sources and informal sources. Each of these categories was further divided into sub-categories. The formal sources included academic education before college, and in college. The informal sources included a host of life experiences: being told by a relative or a friend, watching TV, and similar sources.

In the cross-case mega matrix, I standardized the listing across questions and participants to facilitate locating patterns and identifying sources. Table 4.1 summarizes the sources of knowledge cited by students for each of the questions followed by some examples and notable quotations.

Table 4.1

Sources of Knowledge

Formal	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**
Elem. School	3	3	0	1	4	0	2
H. S. Chem.	15	9	10	10	6	13	8
H. S. Phys.	4	3	4	4	6	8	6
Chemistry 1	15	17	8	15	19	9	25
Chemistry 2	3	4	1	1	2	2	2
Physics 1	6	7	4	6	7	6	11
Physics 2	4	1	3	1	1	2	4
Modern Physics	0	0	0	0	0	3	1
Biology	1	1	1	1	1	0	0
Geology	1	1	2	1	1	1	1
Mechanics	1	0	0	0	0	1	0
Thermodynamics	3	0	0	0	0	1	5
Quantum	0	0	0	0	0	1	2
Optics	1	0	0	0	0	0	0
Phys. Chem.	1	0	0	0	0	0	1
Organ. Chem.	1	2	2	2	3	1	1
Biochemistry	1	1	0	0	0	0	0
Informal							
Research	1	1	3	0	1	1	3
Was told	0	2	0	1	1	1	0
Life experience	8	11	12	17	12	5	8
TV	2	3	1	1	1	0	2
Guess	1	7	3	4	5	2	0
Observing &	5	5	2	3	8	2	1
I do not know	3	6	3	0	6	0	1
I do not remember	2	3	7	0	1	2	1
Making up answers	3	0	0	0	0	0	0

Formal Sources:

A. Before College

a. Elementary School Science:

1. In the context of question 2, SP16 said: "My initial knowledge about surface tension came from my fifth grade science class. I attended a magnet school for science during the fifth and sixth grades, and we did an experiment like this."

b. High School Chemistry. High school chemistry was mentioned at one point or another by almost every student interviewed as a source of knowledge for the answers s/he provided. This characterization was across all academic levels.

c. High School Physics. Several students, particularly those in their first or second physics class at the university level, indicated that the ideas they learned in high school physics were useful in answering the questions. The dependence on the high school physics was not mentioned as often as high school chemistry.

B. In college

a. Physics

I was surprised to notice that not all of the students who have just finished or were finishing at the time of the interview the first course of calculus-based physics considered it as a source of knowledge for the question about the silver spoon in the oven. The last part of the first course of calculus-based physics, often called EP1 by my interviewees, has several chapters devoted to thermodynamics. When the students mentioned EP1 as a source of knowledge, it was primarily in a context of discussing friction. Those who mentioned EP1 in the context of the silver spoon question did not speak favorably about this class as a source to enhance the students' understanding of the thermal properties of matter. As SP22, who had EP1 the semester before the interview, mentioned high school chemistry as his main source of knowledge for his answers about the silver spoon questions, I asked him, "You took EP1 last semester, yet you did not mention it as a source of knowledge in this context. Would you explain that to me?" He said, "We did a small section on thermodynamics about heat engines. To the best of my knowledge, we did not do any study of what happens at the molecular level in that class. We talked about heat engines, efficiencies, and PV = nRT, but we had nothing about the molecular level of matter." The senior physics students mentioned some of the advanced physics classes as sources of knowledge in some contexts, but they could not always explain the connection between the class and the question.

b. Chemistry

Chemistry, particularly what the students referred to as Chem 1, was among the most frequently mentioned sources of knowledge. Some students mentioned other chemistry classes like organic and biochemistry, but that was not nearly as often as the first two chemistry classes. Also, I noticed that the students who mentioned organic chemistry or biochemistry classes as sources of knowledge were enrolled in these classes at the time of the interview.

II. Informal Sources

The informal sources of knowledge were less common among students than the formal sources of knowledge, but they were more common than I anticipated. Examples of informal sources of knowledge were:

A. Being informed by a family member:

1. SP1 said: "When I was a kid, my mother subscribed to Science Magazine. I used to look at the pictures, and she explained some of the stuff to me."
2. SP9 indicated that his main source of knowledge for answering question #1 was being told by his father on the farm. "My ideas about the stuff came mostly from my dad who is a farmer. We learned about physics in the real world. You can see experiments going on like a thousand gallon tank of water with water pilling up before it spills. You can also see the dew on the leaves and observe the beads of water."
3. SP19 indicated that he learned about paint from his father who "explained some of this stuff to me as I helped him in his Western Auto store."

B. Carrying out a procedure or a job:

1 In the context of question 4, SP4, SP5 and SP11 mentioned the fact that they painted walls as their only source of knowledge for the answers they provided. SP11, for example, said: "I painted the house and other things before. That's were I learned about paint."

2 Comparing what happens on the surface of the silver spoon with what happens on the inside, SP10 and SP42 mentioned cooking a turkey in an oven and noticing that the inside is much cooler than the outside. SP10 also mentioned

cooking as his main source of knowledge in question #1 when he described and explained the behavior of oil on water.

3 In discussing Scotch tape, SP11, SP19 said: "I use Scotch tape all the time. Hmmm, I never thought about it before." SP22 said: "I am trying to put together all previous experiences and intuitions I generated about the Scotch tape through years of using it."

4 The shower and the bath tub were mentioned as sources of knowledge by several students, particularly when discussing question 2. SP10 indicated that he learned about the behavior of soap and water in the shower. SP19 also said, "I learned about the behavior of soap and water noticing what happens when I wash my hands. If there was oil on my hands, it would not go away with water alone. With soap it works better because soap makes a solution with water."

5 SP37 indicated that he learned about surface tension mostly from being a fire-fighter. He said: "I learned about surface tension on the job."

C. Research as a source of knowledge:

Seven students, SP2, SP3, SP4, SP15, SP17, and SP31, indicated that they either did, or were involved in, some research activities. Also, being involved in research projects was recognized as being more than a source of knowledge by several students. Three of those who mentioned involvement in research as a source of knowledge also indicated that their involvement in research was what kept them in the Physics Department, as SP31 explicitly said: "If it was not for the fact that I work in Professor's ...laboratory, I would not be in this Department. It is in the research laboratory that I saw the connection and the usefulness of what I learn in physics to the real world."

D. **TV and Entertainment**:

Television and other entertainment programs were mentioned by ten students as a source of knowledge about surface phenomena.

1. SP12 indicated that his understanding of paint and of surface tension were enhanced by watching soap commercials on television.
2. In the context of question 5, SP14 said: " For my answers about the paper, I watched the Discovery Channel, a few times, on paper making and I really enjoyed it." SP24 considered his art hobby and watching TV and science fiction movies as the main source of knowledge for his answers to questions 1 through 5.
3. SP1 and SP4 indicated that they had toys as kids that taught them about surface tension.

4.3 Thematic Analysis

In listing the emerging themes, I decided to follow the advice given in many qualitative methods books like Bogdan and Biklin (1998), Krathwohl (1998), and Miles and Huberman (1994) of giving each emerging theme a memorable name whenever possible. The names which I ascribed to themes were occasionally created by a statement made by some participants that resonated in my head long after they said it, or it was inspired by the literature.

4.3.1 Theme 1

The Bridges

At one point or another while attempting to describe or explain phenomena thirty two of the forty-four student participants utilized analogies. For these students analogies served as bridges connecting what they knew and the phenomena under discussion. The use of analogies has received some attention in the literature. Lakoff (1987) argued that people could only grasp abstract ideas by mapping them on to more concrete ones. Miller (1996) pointed to the centrality of analogy and metaphor in the physical sciences in clarifying arguments and explaining puzzles. Also, Clement (1979, 1981) explained the role of analogy in scientific thinking, and then discussed analogy generation in scientific problem solving. Hamed and Zollman (1996) reviewed and compiled the literature associated with using analogies to teach quantum mechanics. Additionally, in the context of qualitative data analysis, Miles and Huberman (1994) encouraged data analysts to pay attention to analogies and metaphors: "The people we study use metaphors constantly as a way of making sense of their experience. We do the same thing as we examine our data."

Table 4.2 provides a checklist of who invoked analogies and the questions in which the analogies were used.

Table 4.2

Analogies Checklist

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Total	SP level
SP1	xx	x			x	x	x	6	Intermediate
SP2								0	Advanced
SP3	x							1	Advanced
SP4						x	x	2	Advanced
SP5		x			x	x		3	Intermediate
SP6								0	Advanced
SP7	x						x	2	Advanced
SP8						x		1	Beginner
SP9		x						1	Beginner
SP10		x	x		x		x	4	Beginner
SP11								0	Beginner
SP12					x			1	Beginner
SP13			x				x	2	Intermediate
SP14								0	Advanced
SP15	x	x	x	x	xxxx	xx	xx	12	Intermediate
SP16								0	Beginner
SP17							x	1	Advanced
SP18								0	Intermediate
SP19			x		x	x		3	Intermediate
SP20					xx			2	Intermediate
SP21								0	Intermediate
SP22								0	Intermediate
SP23	x		x	x				3	Intermediate
SP24		x	x					2	Intermediate
SP25	x	x	x	x				4	Intermediate
SP26								0	Advanced
SP27			x		x		x	3	Intermediate
SP28					x			1	Intermediate
SP29								0	Beginner
SP30		x			x		x	3	Intermediate
SP31	x		x		x			3	Intermediate
SP32								0	Beginner
SP33					X			1	Beginner
SP34				x				1	Beginner
SP35			x	x				2	Beginner
SP36			x					1	Beginner
SP37		x						1	Beginner
SP38					x	x	x	3	Intermediate
SP39							x	1	Intermediate
SP40		x	xx		x			4	Intermediate
SP41		x						1	Intermediate
SP42							x	1	Beginner
SP43	x				xx			3	Intermediate
SP44								0	Beginner
	9	11	13	5	20	9	12	79	

8 Advanced students (6 analogies), 14 Beginners (13 analogies), 22 Intermediates (60 analogies).

The following is a list of analogies used by the students and the contexts for which students used them.

Question 1:

1. SP1 introduced a surprising analogy when he was describing the behavior of an oil drop on the surface of water. He said: "It looks like a supernova explosion. I see the wave-front expanding. It is very cool."
2. In discussing the microscopic explanation of the oil drop on water SP1 referred to surface tension as the "little skin on top", and as "a wall, a barrier".
3. SP3, whose explanation of why oil spread on water was based on a gravitational argument and never mentioned surface tension in the context of question 1, imagined the oil droplet on the microscopic level as "a punch of marbles stacked up. Then, the marbles would spread out because the attraction they have is not enough to overcome the gravitational pull trying to spread them out."
4. Explaining why oil spread on water SP7 said, "Oil stayed on top of the water because of the surface tension. Oil could not penetrate the surface tension of the water. So, oil acted like when you drop water on a solid surface."
5. SP15 also used surface tension to partially account for the spreading of oil on water, and used a similar analogy as that used by SP7. However, his focus was on the weakness of the surface tension of the oil rather than the strength of the surface tension of the water. He said: "Surface tension is what holds the drop to its shape. When the oil drop landed on water, there was not enough surface tension in the oil to hold it in that droplet shape, so it kind of

spilled. It is just like if you pour water on this table." SP25 and SP31 used the same analogy and said: "It is like putting a drop of liquid on the table."

6. While analyzing why oil spread on water, SP23 thought of boiling oil and water while cooking spaghetti. She said: "Oil and water rebel each other. In fact, while boiling oil and water to prepare spaghetti I noticed that the oil does not stay as a film. After a while oil becomes a bunch of little droplets."
7. SP43 described surface tension by saying: "It is kind of like the skin on pudding. The very surface of water holds it together and naturally wants to maintain that shape."

Question 2:

1. Explaining why the penny with soap could not hold as much water on its surface as the dry penny, SP5 said: "Water will hold itself together better on the dry penny. The soap will affect how water holds itself together because of the way soap is set up. Like when you wash your clothes, the soap on one end grabs the dirt, and the other sticks to the water."
2. Explaining the piling of water on the surface of the penny, SP9 connected that to the images he encountered on the farm like the dew on the leaves and the piling of water in a large tank before it spills out.
3. As SP10 explained why more water could stay on the dry penny than on the one with soap, he said: "Water has two hydrogens and one oxygen. The water molecule is polar because one side is more negative than the other, kind of like a magnet."

4. Explaining why less water could accumulate on the penny with soap, SP15 focused on the fact that the soap had already taken some of the available space. He said: "The penny has a ridge around it. If you put soap on it, it will take the volume and you would not be able to put as much water on the penny. It is like a bowl. If you already have it half full, you will not be able to put as much water in it as when it is empty."
5. SP24 thought that the soap mainly acted as wax and said: "The soap on the penny would act like wax and make the water fall off."
6. SP30 chose the dry penny as the penny which would hold more water on its surface based on friction ideas then said: "Whenever I think of friction, I think of an inclined plane and a string pulling a block up the plane. That is my idea of friction."
7. The discussion of surface tension in the context of question 2 reminded SP37 and SP40 of the bugs that walk on the water and do not pierce through the surface skin.
8. Explaining the behavior of water on soap in question 2, SP25 and SP41 made a connection to question 1. SP41 said: "Water is spreading on the soap just like oil spread on water in the previous question."

Question 3:

1. Trying to imagine what he would see if he looked at the sticking process of the Scotch tape under a very powerful microscope, SP10 said: "The molecules

do not mix. The molecules are not magnetic, but picturing them as little magnets is a good way. Not quite sharing electrons, but the positive ions are attracted to the negative electrons."

2. When explaining the sticking mechanism at the microscopic level, SP13 said: "This is a hard one. I do not know. I can visualize little fingers reaching out and grabbing. But I am not sure that this is what is happening because molecules are not little fingers." SP27 thought of surface molecules as "pointing out like hairs." SP40 introduced a similar analogy and said: "I imagine small spikes that fit in the pores and attach themselves."
3. Explaining how the Scotch tape worked, SP15 thought of a tree with roots. He said: "The adhesive seeps into the pores and crevices. When you lift up, it kind of catches in there, kind of like a tree with roots to hold it in. When you remove the tape, you break some of the adhesive. If you notice, the tape is not as sticky as it was before repeated applications." Then when I asked for more details about the attraction mechanism, he said: "The tape acts more like Velcro or a hook and latch." The Velcro analogy was repeated by SP20, SP23, SP31and SP40. SP20 also imagined that under a powerful microscope she would see the molecules with "projections" acting like hooks.
4. SP19 and SP36 imagined the surface that the Scotch tape is sticking to as a large number of suction cups that try to get the sticky material inside.
5. The Scotch tape reminded SP27 of geological materials. She said: "Oh! This tape is like wet minerals we studied in geology. These minerals are rather

sticky. Some ionic forces are involved in making the minerals stick to each other. The forces are not totally ionic, but a little bit so."

6. SP35 called the adhesion process: "molecules holding hands."

Question 4:

1. As SP15 tried to explain the difference in the behavior of the paint and that of the water on the metallic shelf, he made a connection to question 3. He said: "The paint is acting almost like the tape was acting. The paint is very much what we would see under the microscope if we looked at the tape, with the paint being the adhesive and the shelf being the surface we applied it to." The same connection was made SP23 and SP25.
2. The beading of water on the metal reminded SP34 of waxing her car. She said: "Water on the metal beaded up just like when I waxed my car, water beaded up."
3. SP35 reused the analogy of "molecules holding hands."

Question 5:

1. SP10 connected how a pencil made a mark on the paper to two other physical situations. He said: "When I drag the pencil across the paper, lead comes off. It is not forming a solution, but is it any different from the paint sticking to the wall? I do not believe so. I think it is another form of attraction of the graphite to the carbon paper. I guess another question might be why would an eraser remove the lead from the paper? The reason is that the lead is more attracted

to the eraser than to the paper when you push the eraser with enough pressure."

2. SP1 thought of the pencil and the paper as "Two solid blocks sliding past each other." SP15 used a similar analogy. He said: "It is like two walls rubbing against each other." Also SP38 used a similar analogy and said: "It is like dragging a box across a rough floor."
3. SP5 used an analogy similar to those used by SP1 and SP15 to explain how a pencil leaves a mark on the paper. Then, he connected question 5 and question three. SP5 said, "I would say it is like if you slide a block across the table. The block's kinetic energy goes to heat or friction. The block will heat a little bit, and the table will heat a little bit." Then he added: "I think it was explained to me before and kind of made sense, so I took it as the right answer. Electrons on the surface will be ripped off electrostatically like in the case of the Scotch tape where electrons were ripped off. The bonds between the paper and the graphite would make the graphite stick."
4. Explaining how a pencil leaves a mark on the surface of the paper, SP12 said, "Parts of the surfaces stick out farther, and parts of the surfaces stick in farther. And when you get things like graphite close, they want to fill in. It goes back to friction, which is like moving your hand on a bunch of balls where some are sticking out higher than others."
5. Explaining why graphite stayed on the paper, even if one turned it upside down, SP15 said: "Graphite layers probably become embedded into the paper.

When the graphite layer encounters an imperfection in the paper, it runs into the paper and embeds itself. It is almost like an arrow being shot into a tree."

6. As SP15 explained the absorption of ink by the paper he said: "...The ink is running out of the pen and the paper is absorbing it, kind of like a paper towel." In this analogy SP15 made a connection to a case where the absorption effect is more pronounced.
7. Explaining why the fountain-pen did not leave a clear mark on the transparency, SP15 said: "Ink on the transparency is like water on the metallic shelf in the previous question. It just sits on top. The pores in the plastic are much smaller than the ink molecules." I asked him to clarify what he meant by "pore", and he said: "Pores are not deep holes. They are little ditches, dumps, craters. Ya, they are like microscopic craters in the surface." SP27, SP28 and SP31 used the same analogy.
8. SP5 and SP14 and SP40 likened the tip of the transparency pen to a sponge.
9. Explaining why the transparency pen left a clearer mark on the transparency than the fountain pen did, SP10 thought of the ink in the transparency pen as paint. He said: "It is like paint, and there is thin paint, and there is thick paint. There is a more concentrated solution in the transparency pen than in the fountain pen, that's why it leaves a darker mark." SP20, SP33 and SP43 used a very similar analogy and said: "The ink in the transparency pen is like the paint in the previous question, while the ink in the fountain pen is acting like the water."

10. SP30, SP34, SP38 and SP43 connected the behavior of the ink from the fountain pen on the transparency to the behavior of oil on water. SP43 said: "Ink on the transparency was like the oil on water in the previous question." The same context, however, reminded SP41 of furniture polish.

Question 6:

1. In answering the question, "What happens when an atom hits a sold surface?" SP7 said, "When an atom comes down, it starts feeling repulsive forces. When it hits the surface of the water, it starts pushing the point of impact down. But because water wants to hold its surface intact, water acts like a trampoline. The atom pushes down one point causing the surroundings to go up. If the surface is not broken, it will spring back."
2. Describing the difference between the behavior of a slow and a fast atom hitting a solid surface SP5 said: "A slow atom is like a ball hitting a wall. A fast atom is like a bullet." When SP19 indicated that an atom hitting a solid would deflect, I asked him how he reached that conclusion. He said, "I have no experience with atoms, but I was thinking about what a bullet would do."
3. Analyzing what happens when a flying atom hits a liquid surface, SP15 said, "I guess it depends on the velocity. Surface tension is trying to hold the surface tied together, kind of like a bed-sheet. If you put a drop on the bed-sheet, it is going to sit there. But if you fire it at a high enough velocity, it is going to go through the bed-sheet.
4. When I asked SP8 if an atom would stick better to a rough surface or to a smooth one, she said, "I do not know about atoms, but the graphite in the

previous question stuck better to the rough paper than it did to the smooth transparency. So, if I were to make a choice, I'd say a rough surface." SP15 made the same connection when he said: "It would stick better to the graphite for the same reason the graphite sticks to the paper- friction." Also SP38 made a connection to question 5. She said: " It is kind of like what happened on the transparency. The smooth surface has fewer imperfections where atoms from ink or atoms you are shooting at it, having little holes on the surface, can get stuck in these surface holes."

Question 7:

1. Describing what happens on the surface of the silver spoon as it gets heated, SP1 said: "Silver molecules on the surface of the spoon could fly out, just like boiling water molecules."
2. SP4 imagined the atoms in a solid as balls at the end of springs. (This image is very common in physics and chemistry textbooks at all levels.)
3. SP10, SP13, SP38 and SP42 thought about a turkey in an oven instead of a silver spoon. SP10 said: "When you cook a turkey, you notice that the inside is much colder than the outside."
4. Describing what a person who is shrunk enough to observe microscopic details on the surface that is being heated would see, SP15 said: "An earthquake starts to rumble and shake."
5. SP17 and SP27 indicated that the outside of the spoon would melt first. Then they indicted that their answers were guided by the fact that they noticed ice cubes in soft drinks melt from the outside inwards.

6. Describing what one would observe on the surface of the silver spoon as it gets heated up, SP30 said: "It would be like seeing a fire fight in the dark."
7. Describing what a person shrunk enough to be embedded in a silver surface that is being heated would feel or experience, SP15 said: "He will be hit by electrons. Electrons will be hitting him like tennis balls coming from a tennis balls shooting machine."

Comments on the Analogies:

An analogy typically connects two contexts where one of the contexts is more familiar than the other. The familiar context already exists within the knowledge structure of the learner. While reaching for a possible meaningful connection between the already existing side of the analogy and the novel situation which the learner is faced with, some assimilation of ideas gets built and possible enhancements of mental models could occur. As constructivism postulates, the already existing knowledge can significantly determine what the learner could assimilate. In the context of discussing formation of analogies to explain novel situations, ones ability to formulate analogies can be enhanced by having more previous knowledge. However, the amount of knowledge, as measured by the number of physics classes which a student had previously, was not always an accurate indicator of how many analogies or what kinds of analogies the learner may construct. For example, although the students who have taken three physics classes presented a larger number of analogies per student than the students enrolled in their first physics class did, the students who have finished six or more physics classes introduced fewer analogies per student than did the students who finished three physics classes. Other possible sources of knowledge, such as other science classes particularly chemistry which the student participant has finished, and whether the student chooses to rely only on physics classes to construct the answers must be considered in more details in later studies to account for this possible discrepancy.

As I investigated the analogies for connections and deeper meanings, I came up with two schemes of classifications of these analogies. The first scheme of classification would divide the analogies into two groups; static and dynamic analogies. The first group consisted of connecting one static image to another without elaboration. Students who used the static image connection did not attempt to explain how the two sides of the analogy resembled each other. It was left to the listener to make such connections. For example, stating that surface tension was like a wall without going beyond the static image would qualify for such a classification. The second group connected one dynamic process to another. An example of this type of analogy was explaining the mechanism of adhesion as a tree whose roots went deep into the ground and attached themselves to the surroundings.

The second scheme of classification was based on how students seemed to generate the analogy. Was the analogy memorized from another encounter or class, or was it generated at the spur of the moment to solve the problem at hand? SP35, for example used "molecules holding hands" analogy for questions 3, 4, and 5. She also indicated that this analogy she remembered from high school chemistry. This kind of analogy would be classified as memorized analogy. The second group of analogies were generated during the interview either by making a connection to another question, or simply creating an analogy by connecting various images. Although it would be hard to distinguish between these two types by reviewing interview notes, listening to the interviews would facilitate making such distinctions. As students thought aloud, paused, tried to clarify, and even changed their minds about what they were saying one would be able to follow an interesting process of generating analogies at the spot.

4.3.2 Theme 2

The Chemistry Connection

The second emerging theme was related to the sources of knowledge that the students have indicated. Although High School Chemistry and the Introductory College Chemistry were mentioned as sources of knowledge by thirty-three students, five students (three of whom were advanced students) like SP2, showed some ambivalence about using an argument they learned in a chemistry class while being interviewed by a physicist. SP2 said, "I have a good idea, but I learned it in chemistry. So it could be quite wrong." This resistance to transfer knowledge from one topic to another should be a cause of concern for science educators interested in assisting the students to make connections among their knowledge domains.

Another aspect of this theme was not realizing that the inter-atomic and inter-molecular forces were related to electrostatics. Twelve students attributed many of the interactions to what they called "The chemical force", or "It is a chemistry thing." Even those students who mentioned positive and negative charges attracting each other, like SP10 in the context of question 3, called what was happening "it is a chemical thing."

4.3.3 Theme 3

One explanation fits all, or I will use all explanations.

This theme had two sides. Eight students used the same word or phrase to explain most of the questions and did not explain what that word or phrase meant. SP2, a physics senior for example, used the word "ridges" repeatedly to explain all of the observable, and unobservable surface phenomena. To SP2 every surface had "ridges", which determined the surface behavior. The penny in question 2 had "ridges" to hold water. If a thin film of soap covered the "ridges", then the penny's capacity to hold water would be severely reduced due to the absence of "ridges". The same student described the surface of ordinary paper in question 5 as having "ridges", and these "ridges" enabled the pencil and pen to leave clear marks on the paper. The transparency paper and the shiny paper, on the other hand, had fewer "ridges" and that made it hard for the pencil and pen to leave a mark on these materials. The flying atom in question 6 would get stuck to the rough surface because that surface had more of these "ridges".

SP1 answered questions 1 through 5 talking about "polarity", and "surface tension". He went as far as calling surface tension "the motif of the day." SP5 said, "Paint is thicker than water" when he described the paint in question 4. Then he used the same sentence to explain why paint acted differently from the water. When I asked for microscopic explanation, he also said, "Paint is thicker than water." SP 21 explained the spreading of oil on water in question 1 by saying: "The density of oil is lighter than the density of water. That's why oil stays on top." When I asked her to explain why she predicted that the dry penny would hold more water than the penny with soap, she said, "Water will be repelled by the liquid soap. Hmmm, I am kind of confused now because I don't think that density has very much to do with it." After carrying out the procedure that verified her prediction, she returned to density ideas and said, "... I guess the difference in densities would explain what happened." Also, in questions 4 and 5 she used the words "it bonds" or "it does not bond" to describe and explain all the phenomena involved. SP42 used "the hydrogen bond" in almost all of her explanations.

The other side of this theme was giving several explanations for one question hoping that one explanation would match the situation (7). For example, SP7 almost sounded incoherent when he explained why paint stuck to the surface and water beaded up. He said: "Surface tension – that is why water is beading. With the paint, I guess, it is not that attracted. I do not know. It is so thick. It is easier to stay where it is than to move. It is the force of gravity pulling down, and the forces of the paint on itself are not enough to move it between the force of the paint and the metal, or friction is enough to keep it where it is." Then, when I asked for an explanation on the microscopic scale, he said: "The intermolecular forces, like water when it pulls together; it kind of forms a bead. When gravity is pulling down, it minimizes friction because it is beading up. The paint stays stuck to the metal, so gravity cannot do anything to it. Friction on microscale is like the tape in the previous question is what is keeping the paint stuck."

4.3.4 Theme 4

Description is not explanation

Each of the first five questions contained both a quest for description and for explanation. When I asked for a description, I intended to get "a picture in words" (Webster, 1997). I also wanted to start the student talking about a concrete encounter. Then, in the explanation I wanted to hear the student's account for the observed phenomena. Also, I was interested in detecting if students were predisposed to explain the observations at the microscopic level. Fifteen students, however, did not distinguish between description and explanation, and provided almost the same answers for both, such as in SP5 case who said: "paint is thicker than water" when he described the paint in question 4. Then, he used the same sentence to explain why paint acted differently from the water. And when I asked for microscopic explanation, he also said, "Paint is thicker than water." SP8 described what happened when she dropped oil on water by saying excitedly: "Oh my gosh! It spreads out!" When I asked her to explain why oil spread out, she said, "oil wants to be equally spread out through the whole container."

Six students, like SP9 and SP21 intertwined description, explanation, and inferences when I asked for a description.

4.3.5 Theme 5

We need a translator

In the context of discussing how the Scotch tape worked SP1's answer opened my eyes to a very interesting point. He said: " I recall it has to do with polar stuff." Then, he continued his explanation by describing how glue filled the crevices without utilizing the idea of "polarity" and without mentioning what he meant by "polarity". So, I asked him about what he meant by "polar", and he replied: "It could be electrical, but I doubt it." Then I asked: "Why not electrical?" He said: "If it was electrical, you would probably detect electric fields and stuff because you'd have electric charges." Later he added: "I have never seen a Scotch tape which could not stick to a Van De Graff generator. The stuff is polar, but definitely has nothing to do with electric charges or electric fields."

SP1 learned about polarity in high school chemistry, but he learned about electric charges and fields in the second semester of calculus-based physics which he was enrolled in at the time of the interview. Also in the same context, SP2 did not want to use the phrase "induced charges", because he felt that such a description was only appropriate in physics contexts, but he was using an argument which he learned in chemistry.

The proper use of vocabulary facilitates and eases the communication of scientific ideas. Trowbridge and McDermott (1980) stated that, "Just as it would be a mistake to assume that all misuse of technical vocabulary reflects lack of understanding, it also would be equally erroneous to dismiss without careful probing ambiguous use of technical vocabulary as a mere carelessness."

Physics educators such as Arons (1984) repeatedly suggested to use "idea first and name afterwards." Counter to this idea, many of the students seemed satisfied if they could remember the technical words. Sometimes they did not associate the words with ideas, first or afterwards. Arons referred to the phenomenon of taking refuge from questioning by dropping technical names as erudition. Also, when a student invokes a technical term, s/he may not be referring to the same meaning as a physicist using that same term, as illustrated by the above example. Additionally, two students may use the same term to mean two different things. For example, both SP7 and SP15 used "surface tension" to explain why oil spread on water. Upon further probing, however, it became clear that SP7 was referring to the strength of the surface tension of the water while SP15 was referring to the weakness of the surface tension of the oil.

When I asked for explanations, some students got stuck. They were not searching their minds for explanations, they were looking for the proper terminology. As SP1 started explaining why oil spread on water, he smiled and paused for a few seconds. Then he said: "I forgot my terminology." As I encouraged him try his best, he proceeded to give explanations and introduce whatever terminology he remembered. In the context of Question 7, SP10 said that he was preparing for an exam covering heat transfer. So, I asked him, "How does heat transfer?" In his reply he tried to incorporate symbols and formulas. His explanation, however, was not clarified by his mentioning of symbols and formulas . He said: "It is like energy. Like Q. Ahmm Q, I mean, like temperature. Like PV equals nRT. We just learned about temperature and how heat transfers. Basically, you take, I mean, it varies. Heat is transferred, we just put Q constant. And Q is equal to the change in energy internally plus the work done on the object. So, the work is done through the energy."

Eight students introduced their own terminology when they could not remember the standard vocabulary. When SP9 was explaining why the dry penny could hold more water on its surface than the penny with soap, he could not remember "surface tension", so he introduced the name "the contractive forces of the water." In explaining why the paint stayed in place while water did not, SP22 said, "Oh, I guess paint has a higher coefficient of cohesion." SP10 introduced words that sounded like a Star-Trek episode. When I asked him the follow up question: "What is an atom?" He said: "Atoms used to be the building blocks and the smallest particles known. But now they got quasars, phasers, and masers and what not inside them."

4.3.6 Theme 6

I live in the real world

As SP4, a physics senior, indicated that beads formed when he put water on the metal in question 4, I asked him, "How did these beads form?" He said, " Do you want a macroscopic or a microscopic explanation?" He sounded as if he was choosing between two mutually exclusive options. SP20 asked me a similar question to that asked by SP4 in the context of question 3. As I asked, "How does this sticky substance make the tape stick?" She replied, "You mean, like, on the molecular level?" Throughout the interviews I noticed that students were not predisposed to explain the observed phenomena at the microscopic level. However, after they noticed that I asked for explanations at the microscopic level in each of the first few questions, they started to be more inclined to mention microscopic explanations without being prompted to do so.

Students mentioned life experiences as a source of knowledge more frequently than I anticipated before carrying out this research. In discussing the sources of knowledge for his answers, SP9 said, "We learn physics in the real world." Then he provided several examples of situations when he received explanations from his father for various phenomena which he observed in the farm. SP19 mentioned that the main source of knowledge was from working in his family business. He said, "My parents own and operate a Western Auto store. My dad explains some of these things to me." SP37, who works as a fire-fighter said, "I learned about surface tension at work. We need to add some additive to the water to break its high surface tension which would otherwise slow down the flow of the water."

4.3.7 Theme 7

Fill my mind with formulas, and I will stop asking questions.

The longitudinal nature of the sample facilitated making comparisons between three groups of students. The beginners group, with some subcategories of its own, was mainly students with one physics class finished (at the college level) or being enrolled in their first physics class at the time of the interview. The second category was the group of intermediates. This group consisted of students who had two to five physics classes at the college level. The third group consisted of advanced undergraduate students with five or more physics classes.

Although the advanced physics students manifested a wider technical vocabulary than that possessed by the intermediate students, they did not show more inclination to reason about novel phenomena than the intermediate students did. In this sample of students, the inquisitiveness of the physics students seemed to peak around the time they have finished or were enrolled in second-year level physics classes like modern physics. The following three scenarios occurred as three students attempted to analyze the differences between the fountain pen and the transparency pen in the context of question 5. The first interview was with SP28, who was a senior with a double major of physics and mathematics.

INTV: Why did the transparency pen leave a clearer mark on the transparency than the fountain pen did?

SP28: Because it was specially designed to do so.

INTV: What was special about its design?

SP28: I have no idea.

The second interview excerpt was taken from the interview with SP30 who belonged to the intermediate group.

INTV: Why did the transparency pen leave a clearer mark on the transparency than the fountain pen did?

SP30: Hmmm, maybe it (the transparency mark) will rub off like that of the fountain pen and smug.

[SP30 passed fingers on the mark left by the transparency pen and it did not smudge, so I asked the next question.]

INTV: What compelled you to think that the mark of the transparency pen would smudge?

SP30: Because I always think of the high school teacher who wrote on overhead transparency and rubbed it off with her fingers. No scientific reason, just remembered someone rubbing it off.

INTV: Why did not it rub off, you said that ink just sits on top of the transparency and never gets absorbed?

SP30: That's what I was thinking. So now I have to reconsider my initial thought.

[On the table, I placed four transparency markers of various colors in addition to 20 washable markers, and 12 colored pencils. When I invited SP30 to write his name using the transparency marker he used a green one. The ink in the fountain pen was blue.]

Even though the ink in one is green and in the other is blue, I would not think that would have any difference. I would assume that both were made of the same sources. So, maybe it is the medium that delivered it.

INTV: What do you mean?

SP30: I mean the fountain pen tip compared to the felt tip of the transparency pen.

[SP30 then picked a blue transparency marker and used it to write on the transparency. It smudged.]

SP30: Now I guess I am gonna have to change everything. May be it is the color.

[Now SP30 tried other pens that had different colors but the same kind of tip, and pens that had the same color but different kinds of tips.]

SP30: I have a green with a felt-tip [transparency marker] is not smudging. I have blue with a felt-tip [another transparency marker] that is not smudging. I have blue with the fountain pen and it still smudging. I have a blue felt-tip [not a transparency marker] and that is still smudging. It is not color. It has to be the difference in the tips.

[Silent pause for a few seconds, and looked at the pens and the marks each of them left.]

INTV: What are you thinking?

SP30: Ok, I have the two dry erase projection pens in one hand, did not smudge. Now I have the fountain pen and my Crayola blue in the other and both did smudge. I am trying to formulate why did these [pointing to the pens in his right hand] smudge and these [pointing to the pens in his left hand] did not smudge.

INTV: Ok. What are you coming with?

SP30: I don't know, I have blue color in each hand, and I have a felt tip in each hand. Assuming no difference between these two felt tip ones [blue transparency marker and other blue non-transparency marker], I am very confused right now. This gives me a lot of things to think about. I am trying to draw a reasonable hypothesis why this thing here the way it is. Probably the ink itself is different. I am not sure what my answer is!

The third of these interview excerpts was borrowed from an interview with SP29, who was a freshman enrolled in the first semester of calculus-based physics. (This interview occurred at the middle of the semester.)

INTV: Why did the transparency pen leave a clearer mark on the transparency than the fountain pen did?

SP29: Because of the difference in the ink.

INTV: What difference in the ink?

SP29: [Reluctantly answered and lowered her voice.] The chemical form, it is made of the ink.

Similar patterns of reasoning took place in different contexts and with numerous other students. The patterns of reasoning differences became quite evident.

The intermediates tried more explorations as they experimented with the materials on the table. They tried more variations. For example, they tried to stick the scotch tape to more materials than either the students who enrolled in their first physics class (both majors and non-majors) or the seniors did. The following three scenarios were borrowed from the context of question 3. The first involved SP14, who was a Physics senior and within a semester from graduating.

INTV: Here is some Scotch tape. Please take some and investigate its ability to adhere to other materials.

SP14 [Took a piece of Scotch tape and adhered it to the table, then he quickly raised his head waiting for the question.]

INTV: Why does the Scotch tape stick?

SP14: I do not know. Probably some type of glue.

INTV: How does the glue make things stick?

SP14: The glue adheres to most surfaces. I guess it is its chemical make up, it has a sticky property. I never wondered about glue either. That is another thing I do not know.

INTV: Let me be more specific. What is the attraction mechanism of the tape?

SP14: It is [pause], I am not sure how to describe it. I mean it is not a nuclear force or a magnetic force or something like that. It is a sticky force.

INTV: That's a new force!

SP14: [Laugh].

The second scenario involved SP15, a student from the intermediate group and was enrolled in Physics 3 at the time of the interview.

INTV: Here is some Scotch tape. Please, take some and investigate its ability to adhere to other materials.

SP15: [Took one piece and adhered it to the table, took another piece and adhered it a pencil, and took a third piece and adhered it to a mug.]

INTV: Why does the Scotch tape stick?

SP15: Well, Ammmm, Hummm! I do not know how to answer this question really well.

INTV: Answer any way you can.

SP15: It is not just friction. If there is any friction, it is not just friction alone. If you put the tape on the table, you cannot drag it across. That would suggest there is some friction involved. But if you put the tape on top of this pencil and lift up, then the pencil will be lifted. Friction would not do that. So, unless there is something going on, some interaction, between whatever the material on the tape and the material of the pencil, this lifting would not happen. I am really not sure.

INTV: What do you mean by "material on the tape"?

SP15: Basically it is glue. Some sort of adhesive.

INTV: OK, my question then is: How does glue make things stick?

SP15: Well, the stuff like Elmer's glue, you apply it to the two surfaces and it seeps into the pores and dries and hardens, and that is what holds it together. But this adheres instantly and there is no residue when you take it off your hand or whatever object. And it does not dry. There is nothing about the drying and hardening. But it is possible that it works by the same principle. Whatever this adhesive is, it seeps into the pores, and I guess there would be some friction then. Ahhh, you have a rough surface here, the adhesive kind of seeps in and when you lift it catches down there [SP15 made a drawing]. Kind of like a tree with roots to hold it in. So, because it is possible that when you remove it, you are actually breaking off parts of the adhesive here. I notice that the tape is not as sticky after repeated application to the table. It gets less and less sticky.

INTV: What is the attraction mechanism?

SP15: I would not necessarily say that there is any attraction in the electrical sense because there is no actual pulling as the distance gets smaller. Once you apply it, the adhesive seeps in, and kind of spreads. It is kind of like Velcro, with hook and latch stuff.

The third scenario was borrowed from the same context, but from the interview with SP35, who was enrolled in The Physical World class.

INTV: Here is some Scotch tape. Please, take some and investigate its ability to adhere to other materials.

SP35 (Took a piece of the scotch tape and adhered it to the table.)

INTV: Why does the Scotch tape stick?

SP35: (Laughing) There is something, an adhesive, that makes it stick.

INTV: OK, how does the adhesive make it stick?

SP35: I don't know.

INTV: What do you think is the attraction mechanism?

SP35: I have not thought about it before.

INTV: For everything there is a first time.

SP35: I don't know. I guess (pause) part of it is not wet, but some kind of somewhat wet. Kind of like a little wet.

INTV: OK, how would you explain it to your little brother if he asked you?

SP35: My brother would probably know [Laugh] more than I do.

The previous three scenarios were common. They occurred in various contexts and by other students. Therefore, there was a pattern that could not be easily dismissed or ignored.

In their explanations, the intermediates focused more on providing details, and relied less on terminology or memory than the other two groups did. The intermediates introduced more analogies per interview than either of the other two groups did. Also, in questions where more than one possibility existed like: "What happens when a flying atom hits a liquid surface?" the intermediates thought of more scenarios and possibilities than either of the other two groups did. Additionally, the intermediates produced more drawings per interview than either of the two groups did.

The intermediates seemed more at ease in their discussion, and not as afraid of being "wrong" as the seniors were. The intermediates laughed more often, and seemed like they enjoyed the interviews more than either of the other two groups did. The intermediates were less predisposed to saying: "I do not know" as an answer than either of the other two groups of students. Intermediates paused longer before declaring "I don't know" than either of the other two groups did. And often, even when they said " I don't know" it was followed by an attempt to answer rather than a silence indicating a desire to move to the next question as in the cases of the other two groups.

Comparing the sources of knowledge among the three groups of students was also of interest. The beginners relied mostly on informal sources of knowledge and one or two chemistry classes. The seniors mentioned mostly course work as a source of knowledge with some occasional references to "real life experiences." The intermediates relied almost equally on formal and informal sources of knowledge.

Having said all the above, I would hasten to say that one should not interpret what was said as a claim that advanced physics undergraduate students at Kansas State University were less knowledgeable than the intermediate group. There may be a need to have some occasional discussions and debates of physical phenomena that are not a textbook material and encourage students from various academic levels to participate in such discussions. On the other hand, the textbook curriculum itself may benefit from including more connections to "real world" phenomena.

4.4 Interpretive Analysis

Hayes (1981) defined a problem as: "Whenever there is a gap between where you are now and where you want to be, and you don't know how to find a way to cross the gap, you have a problem." When confronted with a novel situation, students approached the situation in a manner analogous to attempting to solve a problem. On impulse, many students said: "I don't know." The "I don't know" statement would be equivalent to "I do not have an answer to this problem." When the questions were broken into components, and occasionally rephrased, the students gradually started to evaluate their cognitive resources. Memory was the first cognitive resource consulted. The student's mind seemed to be wondering: "Have I seen this exact situation before?" If the answer was yes and some recall occurred, the student considered that a success and reported what his/her memory provided. If the answer was yes, and little or no recall occurred, some signs of frustration became evident, as manifested by quick repetition of "I don't know," or "I cannot remember." Temptation to give up at this stage was not far away for many of the students in the beginners group. Some of the students in the seniors group said they tried to remember if the situation occurred in a certain physics class. If they could not remember the occurrence of the situation in a physics class, they hesitated to rely on remembering an explanation from a chemistry class, or a biology class.

If the memory said: "I do not have this situation stored," the next cognitive alternative for the persistent participants was "what situation similar to this situation do I have stored?" Many students relied on similar situations they encountered in the past. This pattern of approach to analyze the physical situations was consistent with the premises of constructivist epistemology, where the whole background and collection of experiences become important. At this stage, however, I became puzzled by the fact that senior physics students, who had more classes than the intermediate level students, did not manifest more eagerness to analyze the questions in the interview protocol than the intermediate level students. A resolution of this puzzle may be facilitated by realizing that intermediate level students where more willing to rely on other sources of knowledge in addition to physics classes. Also, the senior physics students did not want to be "wrong."

If the memory exhausted its resources without finding the exact situation or a similar situation, the persistent students tried to create an analogy on their own. Then, the students tried to use a newly created analogy to explain the situation at hand. Creating analogies in the context of analyzing a novel situation is very valuable. Clement (1984) studied the strategies of successful physics problem solvers and articulated his conclusion by saying: "In summary, bridging analogies strike us as one of the most insightful and effective strategies for confirming the validity of a model and increasing understanding that we have observed."

Of course, it would be a cause for celebration if all students could establish enough connections and build sufficiently elaborate analogies to resolve all novel encounters. Unfortunately, that is not the case. Several reasons seemed to hinder the ability of students to build bridging analogies and extrapolate beyond what they were taught. First, students did not always remember what they were taught. My tapes are replete with "I don't recall," and "I don't remember." Second, some students never understood what they were expected to understand in the first place. Occasionally, they even rationalized why they did not. SP36 said, "I always felt that physics and chemistry were too hard and boring, and I never wanted to study them." Third, despite our belief that nature itself is an unbroken whole, we unintentionally compartmentalize knowledge by departments on college campuses. Too often, for example, there is a total lack of coordination between what two seemingly related departments teach. From personal experience, I remember asking my professor in the second semester of calculus, "Sir, why did we skip chapter seven which covered the applications of integration to physics and engineering?" His response was, "Well, here we teach calculus, let the Physics

Department teach you physics." I am sure that he was not then, and is not now, the only one with that attitude. An implication of this approach would be to "teach" in a manner that creates separated islands of knowledge in an ocean of ignorance. In this manner, ideas will be hard to assimilate and integrate in any meaningful manner. The fourth reason for the lack of ability of some students to create bridging analogies goes back to the difficulties with vocabulary. When the same physical idea gets two different labels without any hint that there could be a connection between them, and then it is left to the student to create the connections, we should not be too surprised if the connections never get created. A fifth possible cause of the indicated difficulties is the fact that students seem to be actively separating subjects or at least come to the conclusion that physics and chemistry use different models. Thus, a model may be "correct" in physics may not be "correct" in chemistry and vice versa. It is true that students should construct their own knowledge, but it would help this construction if it was supported by some facilitation. Let us find better ways to raise the awareness of the students to the possibility of building bridges between their cognitive domains.

Fourteen students seemed to have a context that they were very familiar with and comfortable talking about. I would label that context as the student's cognitive safety zone. Frequently, students tried to drag any discussion to this safety zone. For example, SP27 - a geology senior- described and explained all of the phenomena in terms of some geological phenomena that she was familiar with. She said that she liked geology very much and she tried to make sense of the phenomena in the questions according to her experiences with geological materials. Although she had several physics and chemistry classes, she only considered geology as her source of inspiration. SP44, who had studied several chemistry classes, finally found her cognitive safety zone to be organic chemistry. She had completed several chemistry classes and she was a pre-veterinary major. She tried to explain every phenomenon, including the silver spoon questions, however, in terms of what she learned in organic chemistry. It may enhance our understanding of how students learn and make connections between cognitive domains if we could understand how students build these cognitive safety zones.

CHAPTER FIVE

IMPLICATIONS AND CONCLUSIONS

5.1 Introduction: Bringing It All Together

Motivated by the need for better integration between research and education, I carried out this research endeavor. I choose to focus on surface phenomena because of their ubiquity. Literally, surfaces are everywhere. There are many "real world" examples which students encounter and that makes the discussion of surface phenomena meaningful. The industrial and technological applications of surfaces are numerous. The semiconductor industry, the computer technology, and the medical applications as in medicine delivery are but a few examples. Yet, despite the importance of understanding surface phenomena, no systematic effort was done before to investigate students' understanding of surface phenomena. Consequently, no systematic effort to provide an introduction to surface phenomena at the undergraduate level was undertaken. The attitude of many of the authors of surface physics/chemistry/science books such as Zangwill (1988) has been that surface science is too advanced for the undergraduate audiences who were considered lacking the background to embark on a discussion of surface phenomena.

In this study, I designed an interview protocol with examples from liquid – liquid, liquid – solid, solid – solid, gas – liquid, and gas – solid interfaces and interactions. I carried out a pilot study with eight participants. The pilot study assisted in validating and refining the protocol questions. Then I interviewed forty-four undergraduate students.

Participation in the study was via invitation and was totally voluntary, and with no compensation or extra credit offered nor given. Participants' involvement in science varied from being enrolled in the least mathematically demanding physics class with no intent to take any more physical science classes, to being a physics senior enrolled in the last semester before graduation with an intent to pursue graduate studies in physics. The sampling was purposeful and provided a valuable longitudinal view. All interviews were audio-recorded, then qualitatively analyzed for themes and patterns. The main focus of the analysis was to better understand how students thought about a complex topic about which they had little direct instruction. The topic in this case was surface phenomena.

5.2 Summary of Findings

Several themes emerged in the students' answers. These themes were:

Theme One: The Bridges.

Students repeatedly used analogies and metaphors to draw some parallel between the phenomena in the question and another phenomena or situation they encountered before. Some analogies were facilitated by the interview questions. For example, some students used the answer they provided for one question as a guide to reason about another question. Some students used gradual or several steps in building an analogy. Their approach was similar to what Clement (1981; 1984) called "bridging analogies." Some of the interview questions seemed to facilitate the use of this bridging approach. For example, In question 5 I provided three pieces of paper with varying level of roughness to write on. SP15 hypothesized that "the notebook paper absorbed the ink better than the transparency and the shiny paper because it was a rougher surface. Then he introduced a fourth level of "roughness" to validate his hypothesis. He said: " We could think of a more extreme case of roughness. The paper towel would absorb even more ink than the regular paper."

Theme Two: "I have a good idea, but I learned it in chemistry. So, it could be quite wrong."

Some students were very reluctant to use ideas they have learned in chemistry and other science classes. They did acknowledge, however, these classes as sources of knowledge. They also tended to indicate some advanced classes like quantum mechanics as an important source of knowledge to explain a particular phenomenon. But they could not explain the connection between some of the advanced class they mentioned and the phenomenon they were trying to explain.

Theme Three: One explanation fits all, or I will use all explanations.

Some students used the same explanations for most of the questions. They have even repeated the same word or words. On the other hand, other students seemed to be on a fishing expedition for an explanation. Hoping that something they said would fit the situation, they tried top say everything that crossed their minds in a style similar to brainstorming.

Theme Four: Description is not an explanation.

Whether I asked for a description or an explanation, many students provided the same answers. Of course, observing a phenomena and reporting the details of what the student saw should be distinguished from attempting to explain, infer, or account for the observed phenomenon using scientific principles.

Theme Five: We need a translator.

The proper use of scientific vocabulary facilitates communication and understanding. This theme has three facets:

First: There is a need for a more unified or at least better translated vocabulary among the scientific disciplines that what exists now.

Second: Students need to have more than vocabulary. More detailed understanding of phenomena is called for.

Third: Some students need to distinguish scientific vocabulary from words in science fiction movies. For example, quasars, phasors, and masers are not constituents of atoms.

Theme Six: I live in the real world.

This theme has two components:

First: Most students, at various levels, showed that they were not predisposed to discussing the "microscopic world" without being prompted to do so, or until they noticed that I asked for explanations at the microscopic level in several questions.

Second: The experiences in the "real world" seemed very helpful to many students in explaining the phenomena in the protocol questions. Working on the farm, or on some job duties were more emphasized by some students as sources of knowledge than the numerous science classes they had taken.

Theme Seven: Fill my mind with formulas and I will stop asking questions.

Prior to this research study I expected the "inquisitiveness" about scientific phenomena to grow at a somewhat steady rate as students take more physics classes. In more mathematical terms, I expected "inquisitiveness" to increase as the student's physics knowledge increases. What I noticed during the interviews and during the analysis did not confirm my initial expectations.

Students showed a noticeable increase in "inquisitiveness" as they advanced from the introductory level to the intermediate level. As they took more classes, they did not sustain the same rate of increase in "inquisitiveness." The level of "inquisitiveness" seemed to peak around the time a student has finished three physics classes at the college level.

During the interviews I observed that intermediate students tried more explorations and variations than the introductory and the advanced students. The intermediate students produced more analogies and drawings than either of the other two categories did. While both the introductory group and the advanced group seemed to be relying heavily on memory as a primary source of answers, the intermediate group used a wider variety of sources of knowledge. Additionally, the students in the intermediate group dwelled longer than the others did on the phenomena without showing signs of frustration.

5.3 Implications for Curriculum and Instruction

The study of surface phenomena does not need to wait until graduate level or beyond. It could be introduced at an undergraduate level without relying on sophisticated mathematical formulation, and without waiting for the students to take a large number of advanced physics classes whose connection to surface phenomena is not necessarily obvious. Students who have completed three physics classes at the university level could be the target audience for some instructional materials discussing surface phenomena. Also here are some notes and recommendations inspired directly by the current research project.

- Throughout the interviews, I noticed that the presence of the hands-on experiments facilitated the discussion that followed. Some students would probably not have said as much as they did about the phenomena if no experiments were on the table. So, I recommend including as many hands on activities as possible in any instructional materials to be developed about surface phenomena.
- Students felt more comfortable discussing a phenomenon when they could relate it to some previous encounter or experience. This was totally consistent with the ideas of constructivism. So, when developing instructional materials, I would recommend emphasizing the "real world" connections. Provide examples, or ask the students to provide examples related to the concepts being discussed. For example, when discussing surface tension, I would use SP9's examples from the farm, SP37's example as a fire–fighter, and SP44's example of a bug walking on water with the help of surface tension. Also, I would look for the toys like those mentioned by SP1 and SP4 that they used as children.
- Students used analogies and metaphors to bridge the gap between situations they were familiar with and situations they were not as familiar with. I would capitalize on this use of analogies. Also I would assist the students in creating bridging steps or stations. For example, moving from the notebook paper to the transparency to the

shiny paper seemed to facilitate discussion about the microscopic composition of these materials.

- The discussion of question seven, where our imaginary person could shrink and then could become embedded into the surface, seemed enjoyable to the intermediate and the advanced students but was frustrating to the introductory group. The motion of atoms on the surface of a metal could be introduced in several ways. Traditionally words or equations were the main mode of communication. However, with Molecular Dynamics and Monte Carlo simulation of metallic surfaces (Rahman, 1995), one could imagine the creation of three levels of demonstrations:
    1. Static images, where a series of static images representing the surface of the metal at various temperatures can be presented.
    2. Dynamic rendering of the motion of the atoms according to the Molecular Dynamics and Monte Carlo simulations.
    3. A Virtual Reality world where the student plays the role of the imaginary figure and takes the place of one of the atoms. Then the student could experience some of the motion and (possibly the forces) which that atom encounters.
- Several students considered being involved in research as a valuable source of knowledge. One student explicitly and strongly emphasized that being involved in research was the main reason for him to stay in the Physics Department. Based on the aforementioned observations, I would make two recommendations:
    1. Increase the involvement of undergraduate physics students in research activities that are meaningful to them, and that help them see the usefulness of physics concepts beyond a textbook and a classroom.

2. Increase the involvement of physics researchers in efforts aimed at introducing their research, both methods and findings, to audiences at various levels. Some physicists are used to communicating mostly to colleagues who have detailed knowledge of the topic. Let them try to simplify the concepts and establish the relevance of these concepts to some undergraduate students at least once in a semester.

5.4 Future Directions

Future research directions could focus on one or more of the following:

1. Based on this research and its findings, develop a set of instructional units about surface phenomena and evaluate the effectiveness of these units.
2. Based on this research and its findings, create a written streamlined survey and present it to a larger number of students at various institutions. The survey may choose to focus on a particular topic like surface tension. The survey may also take an open-ended, or a multiple – choice format.

5.5 Conclusion

Investigating students' concepts of surface phenomena enhanced our understanding of how students approach a novel situation or topic about which they have little direct instruction. The students tended to use bridging analogies and metaphors to make sense of the new situations. Also, they tended to use a variety of sources of knowledge in addition to what they received in formal instruction.

Bibliography

Abraham, M. R., Grzybowski, E. B., Renner, J. W., and Marek, E. A. (1992). Conceptual understandings and misunderstandings of eighth graders of five chemistry concepts found in textbooks. Journal of Research in Science Teaching, **29**, 105-120.

Adamson, A. W. (1990). Physical Chemistry of Surfaces (5th ed.). New York: Wiley.

Albanese, A., and Vicentini, M. (1995). Why do we believe that an atom is colorless? Reflections about the teaching of the particle model, Unpublished Manuscript.

Anderson, J. R. (Ed.). (1981). Cognitive Skills and Their Acquisition. Hillsdale, NJ: Lawrence Erlbaum & Associates.

Arons, A. B. (1976). Cultivating the capacity for formal reasoning. American Journal of Physics, **44**, 834-838.

Arons, A. B. (1977). The Various Language: An Inquiry Approach to the Physical Sciences. New York: Oxford university Press.

Arons, A. B. (1982). Phenomenology and logical reasoning in introductory physics courses. American Journal of Physics, **50**, 13-19.

Arons, A. B. (1983). Students patterns of thinking and reasoning, part one of three parts. The Physics Teacher, **21**, 576-581.

Arons, A. B. (1984a). Students patterns of thinking and reasoning, part two of three parts. The Physics Teacher, **22**, 21-26.

Arons, A. B. (1984b). Students patterns of thinking and reasoning, part three of three parts. The Physics Teacher, **22**, 88-93.

Arons, A. B. (1990). A Guide to Introductory Physics Teaching. New York: Wiley.

Arons, A. B. (1997). Teaching Introductory Physics. New York: Wiley.

Aveyard, R. , and Haydon D. A. (1973). An Introduction to the Principles of Surface Chemistry. London: Cambridge University Press.

Bell, B., Watts, M., and Ellington, K. (Eds.). (1984). The Proceedings of a conference: Learning, Doing and Understanding in Science. London: Secondary Science Curriculum Review. Conference was held 11-13, July 1984.

Benson, D. (1993). Students' preconceptions of the nature of gases. Journal of Research in Science Teaching, 30, 587-597.

Ben-Zvi, R., Eylon, B. R., and Silberstein, J. (1986). Is an atom of copper malleable? Journal of Chemical Education, **64**, 232-234.

Blakely, J. M.(1973). Introduction to the Properties of Crystal Surfaces. Oxford: Pergamon Press.

Blin-Stoyle, R. J. (1997). Eureka! Physics of Particles, Matter and the Universe. London: The Institute of Physics Publishing.

Bogdan, R. C. and Biklen, S. K. (1998). Qualitative Research in Education: An Introduction to Theory and Methods. (3rd ed.). Boston: Allyn and Bacon.

Bogdan, R. and Taylor, S. J. (1975). Introduction to Qualitative Research Methods: A Phenomemological Approach to the Social Sciences. New York: Wiley.

Bonder, G., (1986). Constructivism: A theory of knowledge. Journal of Chemical Education, **63**, 873-878.

BouJaoude, S. (1991). A Study of the Nature of Students' Understanding About the concept of Burning. Journal of Research in Science Teaching, **28**, 689-704.

Boyatzis, R. E. (1998). Transforming Qualitative Information: Thematic Analysis and Code Development. Thousand Oaks: Sage Publications.

Boyer, E. L. (1990). Scholarship Reconsidered – Priorities of the Professoriate. Princton, NJ: The Carnegie Foundation for the Advancement of Teaching.

Britan, G. M. (1978). Experimental and Contextual Models of Program Evaluation. Evaluation and Program Planning, **1**, 229-234.

Brooks, A., Briggs, H., and Bell, B. (1983). Secondary Students' Ideas about Particles. Children's Learning in Science Project-CSSME: University of Leads.

Brown, D. E. and Clement, J. (1989). Overcoming misconceptions by Analogical Reasoning: Abstract Transfer Versus Explanatory Model Construction. Instructional Science **18**, 237-261.

Byrnes, J. P. (1996). Cognitive Development and Learning in Instructional Contexts. Boston: Allyn and Bacon.

Cantu, L. L. and Herron, J. D. (1978). Concrete and Formal Piagetian Stages and Science Concept Attainment. Journal of Research In Science Teaching, **15**, 135-143.

Center for Teaching and Learning of Stanford University. (1996). From Research *or* Teaching to Research *and* Teaching. Speaking of Teaching, 7, 1-5.

Christians, D. G. and Carey, J. W. (1989). The Logic and Aims of Qualitative Research. in G. H. Stempel and B. H. Westly (Eds.). Research Methods in Mass Communication. (2nd ed.). pp 354-374. Englewood Cliffs, NJ: Prentice-Hall.

Clegg, V. (1995). Principles of College Teaching. Unpublished lecture notes.

Clement, J. (1979). Mapping a student's causl conceptions from a problen solving protocol. In J. Lochhead and J. Clement (Eds.). Cognitive Process Instruction. Philadelphia, Pennsylvania: Franklin Institute Press.

Clement, J. (1981). Analogy Generation in scientific problem solving. Third Annul Meeting of the Cognitive Science Society. Berkeley, CA, 1981.

Clement, J. (1982). Students' preconceptions in introductory mechanics. American Journal of Physics, 50, 66-71.

Cobb, P., Yackel, E. and Wood, T. (1992). A Constructivist alternative to the representational view of mind in mathematics education. Journal for Research in Mathematics Education, **23**, 2-33.

Coffey, A. and Atkinson, P. (1996). Making Sense of Qualitative Data: Complimentary Research Strategies. Thousand Oaks: Sage Publications.

Collins, K. F., Jones, B. L., Sprod, T., Watson, J. M., & Fraser, S. P. (1988). Mapping development in students' understanding of vision using a cognitive structural model. International Journal of Science Education, **20**, 45-66.

Committee on Condensed -Matter and Materials Physics -CCMMP. (1997). The Physics of Materials: How Science Improves Our Lives. Washington, D.C.: National Academy Press.

Creswell, J. W. (1998). Qualitative Inquiry and Research Design: Choosing Among Five Traditions. Thousand Oaks, Calf: Sage Publications.

Davison, S. G. and Steslicka, M. (1992). Basic Theory of Surface States. Oxford: Oxford University Press.

Denzin, N. K. (1970). The Research Act: A Theoretical Introduction to Sociological Methods. Chicago: Aldine.

Denzin, N. K. and Lincoln, Y. S. (1994). Introduction: Entering the Field of Qualitative Research. In N. K. Denzin and Y. S. Lincoln (Eds.). Handbook of Qualitative Research. pp 1-17. Thousand Oaks, CA: Sage Publications.

De Vos, W. and Verdonk, A. H. (1987). A New Road to Reactions: Part 5, the Element and Its Atoms. Journal of Chemical Education, **64**, 1010-1013.

Dow, W. M. et al. (1978). Pupils' Concepts of Gases, Liquids and Solids. Dundee: Northern College of Education.

Driver, R. and Engel E. (1985). Secondary students' conceptions of the conduction of heat: bringing together scientific and personal views. Physics Education, **20**, 176-181.

Duit, R. (1991). Students' conceptual frameworks: Consquences for learning science. In S. Glynn, R. Yeany, & B. Britton (Eds.). The Psychology of Learning Science. (pp. 65-85). Hillsdale, NJ: Lawrence Erlbaum.

Dykstra, D. I. (1992). Studying conceptual change. In: Duit, R., Goldberg, F., & Niedderer, H. (Eds.), The Proceedings of the International Workshop on Research in Physics Education: Theoretical Issues and Empirical Studies. Bremen, Germany, March 4-8, 1991. Kiel, Germany: IPN.

Ely, M. (1991). Doing Qualitative Research: Circles within circles. London: The Falmer Press.

Erickson, G. L. (1979). Children's Conceptions of Heat and Temperature. Science Education. **63**, 221-230.

Erickson, G. L. (1980). Children's Viewpoints of Heat: A Second Look. Science Education, **64**, 323-336.

Evans, C. & Associates (1999). Advancing Hard Drive Performance. A brochure of Charles Evans & Associates Company.

Feynman, R. P. (1962). Feynman Lectures on Physics. New York: Addison – Wesley Publishing Company, Inc.

Frankel, F., & Whitesides, G. M. (1997). On the Surface of Things: Images of the Extraordinary in Science. San Francisco: Chronicle Books.

Frechtling, J. and Sharp, L. (1997). User-Friendly Handbook for Mixed Method Evaluations. National Science Foundation.

Fuller, R. G., Karplus, R., and Lawson, A. E. (1977). Can physics develop reasoning? Physics Today, **30**, 23-28.

Gabel, D. L. and Bruce, D. M. (1991). Improving Chemistry Achievement Through Emphasis on the Particulate Nature of Matter. Proceedings of the 64th Annual NARST Conference. Lake Genva, Wisconsin.

Gabel, D. L., Samuel, K. V., and Hunn, D. (1987). Understanding the Particulate Nature of Matter. Journal of Chemical Education, **64**, 695-697.

Gallaghar, J. & Raid, D. (1981). The Learning Theories of Piaget and Inhelder. New York: Brook and Cole Publishing Co.

Gibran, K. (1984). The Prophet: A Poem. In B. Bell, , M. Watta, & K., Ellington. (Eds.). Learning, Doing and understanding in Science: The Proceedings of a Conference held near Wakerfield, July 11-13 1984.

Glaser, B. G. & Strauss, A. L. (1967). The Discovery of Grounded Theory: Strategies for Qualitative Research. Chicago: Aldine.

Gould, H. and Tobochnik, J. (1988). An Introduction to Computer Simulation Methods: Applications to Physical Systems. New York: Addison-Wesley Publishing Company.

Glasersfeld, E. V. (1984). An Introduction to Radical Constructivism. In: The Inverted Reality. Watzlwaick, P. (Editor). New York: Norton.

Glasersfeld, E. V. (1989). Constructivism in Education. In T. Husen, and T. N. Postlewhaite, (Eds) The International Encyclopedia of Education, Supplemental Vol. 1 London: Plenum Press.

Glasersfeld, E. V. (1996). Radical Constructivism: A Way of Knowing and Learning. London: The Falmer Press.

Green, M. (1973). Solid State Surface Science. New York: Marcel Dekker, Inc.

Griffiths, A. K., and Preston, K.R. (1989). An Investigation of Grade 12 Student's Misconceptions Relating to Fundamental Characteristics of Molecules and Atoms. Proceedings of the 62nd Annual NARST Conference. San Francisco, California.

Haidar, A. H. and Abraham, M. R. (1991). A Comparison of Applied and Theoretical Knowledge of Concepts Based on The Particulate Nature of Matter. Journal of Research in Science Teaching, **28**, 919-938.

Guba, E. G. and Lincoln, Y. S. (1989). Fourth Generation Evaluation. Newbury Park, CA: Sage Publications.

Hake, R. R. (1996). Evaluating Conceptual Gains in Mechanics: A Six-Thousand Student Survey of Test Data. Paper submitted to the International Conference on Undergraduate Physics Educaion, Univ. of Maryland, College Park, Maryland,.

Halloun, I. A.,& Hesteness, D. (1985). The Initial knowledge state of college physics students. American Journal of Physics, **53**, 1043 – 1055.

Hamed, K. M. and Zollman, D. A. (1996). Using analogies to teach quantum mechanics. A Paper delivered at the 1996 Summer AAPT Conference, University of Maryland.

Hammer, D. (1996). More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. American Journal of Physics, **64**, 1316 – 1325.

Hashway, R. M. and Duke L. I. (1992). Cognitive Styles: A Primer to the Literature. New York: The Edwin Mellen Press.

Hayes, J. R. (1981). The Complete Problem Solver. Philadelphia: Franklin Institute Press.

Helm, H. & Novak, J. (Eds). (1983). Misconceptions in Science and Mathematics. Proceedings of International Seminar on Misconceptions in Science and Mathematics. Held June 20-22, 1983. Ithaca, NY: Department of Education, Cornell University.

Hesteness, D. (1987). Toward a Modeling Theory of Physics Instruction. American Journal of Physics, **55**, 440-454.

Hesteness, D., Wells, M., and Swackhammer, G. (1992). Force Concept Inventory. The Physics Teacher, **30**, 141-158.

Holliday, W. (1975). The Effects of Verbal and Adjunct Pictorial-Verbal Information in Science Instruction. Journal of Research in Science Teaching, **12**, 77-83.

Hudson J. B. (1998). Surface Science: An Introduction. New York: John Wiley & Sons, Inc.

Jankowski, N. W. and Wester, F. (1991). The Qualitative Tradition in Social Science Inquiry: Contributions to Mass Communications Research. In K. B. Jensen and N. W. Jankowski (Eds.) A Handbook of Qualitative Methodologies for Mass Communication Research, pp 44-74. New York: Routledge.

Jensen, K. B. and Jankowski, N. W. (Eds.) (1991). A Handbook of Qualitative Methodologies for Mass Communications Research. New York: Routledge.

Johnson, P. (1998). Progression in children's understanding of a 'basic particle theory: a longitudinal theory. International Journal of Science Education, 20, 393-412.

Kaplan, A. (1964). The Conduct of Inquiry. Scrnton, PA: Chandler.

Karplus, R. (1977). Science teaching and the development of reasoning. Journal of Research in Science Teaching, **14**, 169-175.

Kirk, J., and Miller, M. L. (1996). Reliability and Validity in Qualitative Research. Beverly Hills, CA: Sage.

Klausmeier, H. J., Ghatala, E. S., and Frayer, D. A. (1974). Conceptual Learning and Development: A Cognitive View. New York: Academic Press.

Krathwohl, D. R. (1998). Methods of Educational and Social Science Research: An Integrated Approach. (2nd ed.). New York. Longman Publishing Group.

Kuhn, T. S. (1970). The Structure of Scientific Revolutions. Second Edition. Chicago: University of Chicago Press.

Kuhn, D. (1989). Children and adults as intuitive scientists. Psychological Reviews, **96**, 674 – 689.

Kvale, S. (1996). InterViews: An Introduction to Qualitative Research Interviewing. Thousand Oaks: Sage Publications.

Lawson, A. E. (1982). The Reality of General Cognitive Operations. Science Education, **66**, 229-238.

LeCompte, M. D., Millroy, W. L., Preissle, J. (Eds.). (1993). The Handbook of Qualitative Research in Education. San Diego: Academic Press

Lewins, J. D. (Ed.). (1984). Teaching Thermodynamics: Proceedings of a conference held Sept 10 – 21, 1984 at Emmanuel College, Cambridge, England. New York: Plenum Press.

Lewis E. L. and Linn, M. C. (1994). Heat Energy and Temperature Concepts of Adolescents, Adults, and Experts: Implications for Curricular Improvements. Journal of Research in science Teaching, **31**, 657-677.

Lijnse, P. L., Licht, P., Vos, W., & Waarlo, A. J. (Editors) (1990). Relating macroscopic phenomena to microscopic particles: a central problem in secondary science education. Proceedings of a conference held at the University of Utrech, July 1990. Utrech, Netherlands, CD-ß Press.

Lincoln, Y. S. and Guba, E. G. (1985). Naturalistic Inquiry. Newbury Park, CA: Sage Publications.

Lindlof, T. R. (1991). The Qualitative Study of Media Audiences. Journal of Broadcasting and Electronic Media, **35**, 23-42.

Lindlof, T. R. and Meyer, T. P. (1987). Media Use as Ways of Seeing, Acting, and Constructing Culture: The Tools and Foundations of Qualitative Research. In Lindlof (Ed.). Natural Audiences: Qualitative Research of Media Uses and Effects, pp. 1-30, Norwood, NJ: Ablex.

Luchner, K., Derger, H., Dengler, R., & Wong, R. (1988). (Editors). Teaching Modern Physics: Proceedings of a Conference held Sept 12 – 16, 1988, at Munich University. London: World Scientific.

Marshall, C. and Rossman, G. B. (1989). Designing Qualitative Research. Newbury Park, CA: Sage Publications.

Marton, F. (1986). Phenomenography – A Research Approach to Investigating Different Understandings of Reality. Journal of Thought, **21**, 28-49.

Maxwell, J. A. (1996). Qualitative Research Design: An Interactive Approach. Thousand Oaks, CA: Sage Publications.

McDermott, L. C. (1984). Research on conceptual understanding in mechanics. Physics Today, **37**, 24-32.

McDermott, L. C. (1991). What We Teach and What Is Learned: Closing the Gap. American Journal of Physics, **59**, 301-315.

McDermott, L. C., & Shaffer, P. S.(1992). Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding. American Journal of Physics, **60**, 994-1003.

Mestre, J., & Touger, J. (1989). Cognitive research – What's in it for physics teachers? The Physics Teacher, **27**, 447-456.

Michelini, M., Jona, S. P., and Cobai, D. (1996). Teaching the Science of Condensed Matter and New Materials: Proceedings of a conference held August 24 – 30, in Udine, Italy. Udine: Forum.

Miles, B. M., & Huberman, A. M. (1994). Qualitative Data Analysis: An Expanded Sourcebook. Second Edition. Thousand Oaks: Sage Publications.

Morse, J. M. (Ed.). (1997). Completing a Qualitative Project: Details and Dialogue. Thousand Oaks: Sage Publications.

Moshman, D. (1990). Rationality as a goal of education. Educational Psychology Review, **2**, 335-364.

Myers, H. P. (1990). Introductory Solid State Physics. New York: Taylor & Francis.

Niedderer, H. (1987). A Teaching Strategy Based on Students' Alternative Frameworks-Theoretical Conceptions and Examples. in Duit, R., Goldberg, F. and Niederer, H. (Eds.) Misconceptions and Educational Strategies in Science and Mathematics: Cornell University, Ithaca, NY, pp. 360-367.

Novak, J. D. (Editor) (1987). Proceedings of the Second International Seminar on Misconceptions and Educational Strategies in Science and Education. Conference was held at Cornell University, Ithaca, NY during the period: July 26-29, 1987.

Nussbaum, J. and Novick, S. (1982). Alternative Frameworks, Conceptual Conflict and Accommodation: Toward a principled Teaching Strategy. Instructional Science **11**, 183-200.

Novick, S. and Nussbaum, J. (1981), "Pupil's Understanding of the Particulate Nature of Matter: A Cross-age Study", Science Education, **65**, 187-196.

O'Kuma (1997). Efforts in Revitalizing the Introductory Physics Class. A Paper given at the AOK section of the AAPT Conference in Oct, 1997.

Osborne, R. J. and Cosgrove, M. M. (1983). Children's Conceptions of the Change of State of Water. Journal of Research in Science Teaching, **20**, 825-838.

Osborne, R., Cosgrove, M. and Schollum, B. (1982). Chemistry and the Learning Science Project. Chemistry in New Zealand, **46**, 104-106.

Patton, M. Q. (1990). Qualitative Inquiry and Research Methods. Beverly Hills, CA: Sage Publications.

Pauly, J. J. (1991). A Beginner's Guide to Doing Qualitative in Mass Communication. Journalism Monographs, 125.

Peterson, R. F., Treagust, D. F., and Garnett, P. (1989). Development and Application of A Diagnostic Instrument to Evaluate Grade 11 and 12 Student's Concept of Covalent Bonding and Structure Following a Course of Instruction. Journal of Research in Science Teaching, **26**, 301-314.

Pfundt, H. and Duit, R. (1987). Bibliography: Students' alternative frameworks in science education, Second Edition. Kiel: IPN.

Pirie, S. & Kieran, T. (1992). Creating constructivist environments and constructing creative mathematics. Educational Studies in Mathematics, **23**, 505-528.

Potter, W. J. (1996). An Analysis of Thinking and Research about Qualitative Methods. New Jersey: Lawrence Erlbaum Associates.

Pressly, M., et. al. (1994). Transactional instruction of comprehension strategies. Reading and Writing Quarterly, **10**, 5-19.

Prutton, M. (1994). Introduction to Surface Physics. Oxford: Oxford University Press.

Rahman, T. S. (1995). Dynamics and structure at metal surfaces- A Molecular Dynamics study. Condensed Matter Theories, **9**, 299-313.

Redish, E. F. (1994). The implications of cognitive studies for teaching physics. The American Journal of Physics, **62**, 796-803.

Redish, E. F., Saul, J.M., and Stienberg, R.N. (1998). Student expectations in introductory physics. The American Journal of Physics, **66**, 212-224.

Redish, E. F and Steinberg (1999). Teaching Physics: Figuring out what works. Physics Today, **52**, 24-30.

Reif, F. (1987). Instructional design, cognition, and technology: Applications to the teaching of scientific concepts. Journal of Research in Science Teaching, **24**, 309-324.

Robson, C. (1993). Real World Research: A Resource for Social Scientists and Practitioner-Researchers. London: Blackwell.

Roth, W. (1994). Experimenting in a constructivist high school physics laboratory. Journal of Research in Science Teaching, **31**, 197-223.

Roth, W. (1998). Learning process studies: examples from physics. International Journal of Science Education, **20**, 1019-1024.

Rouhi, A. M. (1999). Contemporary Biochemicals. Chemical and Engineering News, **77**, 51-58.

Rubin, H. J. and Rubin, H. J. (1995). Qualitative Interviewing: The Art of Hearing Data. Thousand Oaks: Sage Publications.

Sayer, A. (1992). Methods in Social Science: A Realist Approach. (Second Edition). London: Routledge.

Scott, P.H., Asoko, H.M., & Driver, R. H. (1991). "Teaching for conceptual change: A review of strategies," In Duit, R., Goldberg, F., & Niedderer, H. (Eds.), The Proceedings of the International Workshop on Research in Physics Education: Theoretical Issues and Empirical Studies .Bremen, Germany, March 4-8, 1991. Kiel, Germany: IPN.

Shaffer, P.S., & McDermott, L.C. (1992). Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies. American Journal of Physics, **60,** 1003-1013.

Sharpe, S. W. (1978). Atoms and Matter: Bonding, Structure, and Property. Toronto: Wiley Publishers of Canada Limited.

Somorjai, G. A. (1994). Introduction to Surface Chemistry and Catalysis. New York: John Wiley & Sons, Inc.

Somorjai, G. A. (1996). Modern Surface Science and Surface Technologies: An Introduction. Chemical Reviews, **96,** 1223-1235.

Somorjai, G. A. (1998). The Flexible Surface. Journal of Chemical Education, **75,** 161-176.

Staver, J. (1986). The constructivist epistemology of Jean Piaget: Its philosophical roots and relevance to science teaching and learning. Paper presented at the United Stated-Japan seminar on Science Education, Honolulu, Hi., Sep 14-20, p.28.

Stofflett, R. T. (1994). The accommodation of science pedagogical knowledge: The application of conceptual change constructs to teacher education. Journal of Research in Science Teaching, **31**, 787-810.

Strauss, A., & Corbin, J. (1990). Basics of Qualitative Research: Grounded Theory Procedures and Techniques. Newbury Park: Sage Publications.

Swartz, C. E. and Miner, T. (1997). Teaching Introductory Physics: A Sourcebook. New York: AIP Press.

Tally, L. H. (1973). The Use of Three-Dimensional Visualization as a Moderator in the Higher Cognitive Learning of Concepts in College Level Chemistry. Journal of Research in Science Teaching, **10,** 262-269.

Thornton, R. K. and Sokoloff, D. R. (1990). Learning Motion Concepts Using Real-Time Microcomputer Laboratory Tools. American Journal of Physics, **58,** 858-867.

Tobin, K. & Lorshback, A. (1992). Constructivism as a reference for science teaching. NARST News, **30,** 1-3.

Trowbridge,D. E. & McDermott, L. C. (1980). Investigation of Student Understanding of the Concept of Velocity in One Dimension. American Journal of Physics, **48**, 1020-1028.

Turner, J. (1984). Cognitive Development and Education. New York: Methuen & Co.

Unal, R.(1996). An Investigation on How Students Describe an Atom: A Phenomenographic Approach. Unpublished Masters Thesis, Kansas State University.

Unal, R. and Zollman D. Z. (1999). An Investigation on How Students Describe an Atom: A Phenomenographic Approach. Unpublished manuscript.

Viennot, L., & Rainson, S. (1992). Students' reasoning about the superposition of electric fields. International Journal of Science Education, **14**, 475-487.

Watts, M., & Taber S. K. (1996). An explanatory gestalt of essence: students' conception of the 'natural' in physical phenomena. International Journal of Science Education, **18**, 939-954.

Webster (1997) – *The Dictionary.*

Wells, M., Hestenes, D., & Swakhmaer,G. (1995). A modeling method for high school physics instruction. American Journal of Physics, **63**, 606-619.

West, L. T. and Pines, A. L. (Eds.). (1985). Cognitive Structure and Conceptual Change. New York: Academic Press.

Williamson, V. M. and Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of College Chemistry students. Journal of Research in Science Teaching, **32**, 521-534.

Wilson, J. (Ed.). (1997). Conference on the Introductory Physics Course. New York: Wiley.

Wolcott, H. F. (1982).If It Isn't Ethnography, What Is It? Review Journal of Philosophy and Social Science, 7, 154-169.

Yarroch, W. L. (1985). Students' Understanding of Chemical Equation Balancing. Journal of Research in Science Teaching, **22**, 449-459.

Zangwill, A. (1988). Physics at Surfaces. Cambridge: Cambridge University Press.

Zeidler, D. L. and McIntosh, W. J. (1989). The Effectiveness of Laser Disc Generated Models on Conceptual Shifts in College Students. Proceedings of the 62nd Annual Narst Conference. San Francisco, California.

Appendix #1

The Interview Protocol

Interview Protocol
Investigating Students' Concepts of Surface Phenomena.

By
Kastro M. Hamed
Advisor: Professor Dean A. Zollman

Introduction:

First, I would like to welcome you to this interview. The purpose for this interview is collect information on how physics students describe and explain some physical phenomena. Later we hope to create some instructional materials to help students learn more about these and similar phenomena. You will not be graded, and whatever you say here will remain confidential.

Second, the Human Subjects Committee at KSU requires us to obtain your signature agreeing to being interviewed. Also, since it would be more practical to use an audio recorder than just take notes, a tape recorder will be used. I hope that its presence will not distract you.

Here is the Consent form, please read it and provide your signature indicating your approval.

Follow-up questions should cover:

1. Probing into the students' background, and level in their major.
2. Asking questions related to atoms, molecules, etc. (Based on the discussion of progress report talk).

(You are encouraged to draw pictures whenever you think that would help you clarify your explanations. We have colored pens, pencils and white paper for your use.)

Q1) On the table we have a transparent container with some water in it. We also have a dropper and some olive oil. Please use the dropper to take some oil, and drop one droplet of oil on the water. Then

Describe what happened.

Explain why the oil droplet acted the way it did.

On the microscopic level, what do you think happened to the oil droplet?

What Knowledge did you use to reach that conclusion?

Where did you learn that?

Q2) Now, I'd like you to make a prediction. We have two pennies, a dropper, liquid soap, and some paper towels. If you use the dropper to put water drops on the surface of a penny, will you be able to put more drops on the surface of a dry penny, or on the surface of the penny which has a thin film of liquid soap on it?

Explain your reasoning.

What knowledge did you use to reach that conclusion?

Where did you learn that?

Now carry out the procedure, with the dry penny first and count the number of drops.

Now explain the difference in the two cases at the molecular level.

Again, what knowledge did you use to reach that conclusion?

Where did you learn that?

Q3) Use some scotch tape, and investigate the ability of this material to adhere to other materials, then answer the following questions:

Why does the scotch tape stick?

[If the interviewee says: "because there is glue", then the second question will be: and how does glue make things stick?]

What is the attraction mechanism?

If you looked at the sticking process under a very powerful microscope, what would you see?

What knowledge did you use to reach that conclusion?

Where did you learn that?

Q4) For this question we will use this piece of metal (part of an old shelf), some paint and two small brushes. With some paint on one of the brushes write the letter "S" on the metal. Then with water on the other brush write the same letter on the metal (a different spot, of course). Then

Describe and compare what happened in the case of the paint then in the case of the water.

Explain the differences.

On the microscopic scale, what caused the differences which you indicated?

What knowledge did you use to reach that conclusion?

Where did you learn that?

Q5) Here is a piece of white paper and a pencil. Please use the pencil to write your name on the paper. Explain the mechanism for the pencil to leave a mark on the paper.

Use the pencil to write your name on the shiny piece of paper, and on the transparency. Describe what you see on the three materials.

Explain any differences, at the microscopic level.

Next you will repeat the process, except this time you will use a pen instead of the pencil. Explain the mechanism for the pen to leave a mark on these materials.

What is happening here at the microscopic level?

Explain any differences.

Here is what is called a transparency pen. Write your name on the three materials again.

Describe what happened in this case.

Why does the transparency pen leave a clearer mark on the transparency than the other pen?

What knowledge did you use to reach that conclusion?

Where did you learn that?

Q6) What happens when a flying atom hits a liquid surface?

What happens if the same kind of atom hits a solid surface?

If an atom hits a surface, will it have a better chance to stick to a rough surface, or to a smooth one? Explain your answers providing as much details as possible.

What knowledge did you use to reach that conclusion?

Where did you learn that?

Q7) Imagine that we put a silver spoon in an oven which is totally empty otherwise. Then we use a knob to gradually increase the temperature inside the oven.

What happens to the spoon as the temperature is increased?

What happens to the surface of the spoon as the temperature is increased?

Do you think that there is any difference between what happens inside the body of the spoon and on its surface as the temperature is increased? Explain.

If one could shrink himself to a really small size, what would he see at the surface of the spoon as the temperature is increased?

Now if one was shrunk to the point where he could be embedded within the surface, what would he feel as the temperature is increased?

What knowledge did you use to reach that conclusion?

Where did you learn that?

Appendix #2

Informed Consent Document

Informed Consent Document

A) Subject Orientation:

Please read the following, and sign below if you accept the terms explained herein.

You are asked to take part of this research study whose aim is to analyze students' concepts of some physical phenomena. Based on this analysis instructional materials will be developed. The procedure here is an approximately thirty minute interview which will be recorded and analyzed. There are no foreseeable risks involved. You are assured full confidentiality. No report, oral or written, will reveal your name or identity.

B) Informed Consent:

I have read the forgoing Subject Orientation and agree to take part in the study. My participation is purely voluntary. I understand that my refusal to participate will involve no penalty or loss of benefits to which I am otherwise entitled and that I may discontinue participation at any time without penalty or loss of benefits to which I am otherwise entitled.

If I have questions about the rationale or method of the study, I understand that I may contact Professor Dean A. Zollman

503 Cardwell Hall
Kansas State University
Manhattan, Kansas, 66506
(785) 532-1619/1612
dzollman@phys.ksu.edu

If I have questions about the rights of subjects in this study or about the manner in which the study is conducted, I may contact Clive Fullagar, Chair, Committee on Research Involving Human Subjects, 103 Fairchild Hall, Kansas State University, Manhattan, Kansas, 66506, at (785) 532-6195.

Signature:

Date:

Appendix #3

Tips for a Good Interview

Tips for a Good Interview:

Assimilated by Kastro M. Hamed
based on reflections after conducting the pilot study and on
(Bogdan & Biklen, 1998), (Krathwohl, 1998), (PER, 1998), and EDADM 886(Professor Salsberry).

Before the Interview:

1. Prepare questions that match the purpose of your study, and how structured you want the interview to be.
2. Ask a friend, colleague, or professor to read the questions and provide some feedback.
3. Rewrite the questions based on feedback.
4. Pilot the interview for large studies.

During the Interview:

At the Beginning:

1. Check recording equipment, and other materials involved in the interview.
2. Start with a small talk to develop rapport.
3. Briefly inform the interviewee of your purpose, and make confidentiality assurances.
4. Ask the interviewee to sign the Informed Consent Document.

During the Interview:

1. Avoid rigid control of the content.
2. Avoid the use of questions requiring only yes/no responses.
3. Question for clarity, not to challenge.
4. Be flexible.
5. Avoid exploiting the trust of the interviewee.
6. Avoid evaluative remarks.
7. Capture interviewee's language (through recording, and notes).
8. Avoid feeding responses.
9. Try for asymmetrical turn taking.
10. Express interest.
11. Repeat and incorporate interviewee's terms in follow up questions.
12. Ask one question at the time.
13. Good interviewing involves deep listening. Good listening stimulates good talking.
14. Do not fear silence.
15. Treat the person you are interviewing as an expert.
16. Never record without permission.

At the End of the Interview:

1. Discuss the possibility of future interviews as needed.

2. Thank the interviewee, and take leave!

After the Interview:

1. Write field notes immediately, if you could not take them during the interview.
2. Carefully label & file the material (tapes, notes, etc), in an organized manner.
3. Write your reflections regarding the interview, and its contents.
4. Start the looong journey of data analysis, (actually you already started).