# PUTTING RATIONAL CONSTRAINTS ON DIVERGENT THOUGHT: THE DEVELOPMENT OF SCIENTIFIC REASONING

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# DEDICATION

*I guess I shouldn't think it odd until we see the face of God*
*The yearning deep within us tells us there's more to come.*
*So when we taste of the divine, it leaves us hungry every time*
*for one more taste of what awaits when heaven's gates are reached.*
*I believe that's what Heaven is for.*

(Arends, 1995)

**My family...**
...whose unfailing confidence and pride, high expectations, permission to make mistakes, encouragement to learn from them, and certainty of love no matter what else happens give me the strength and the will to persevere.

**A special friend...**
...Simone, whose interest in and interaction with my work has helped me to stay interested during the times when nothing seemed to be making sense.

**My mentors...**
...who hear my scuffling feet, open doors that lead me past the safety of friends and family, and invite me to places I would never presume to belong.
Thank you for believing in me:
Monica S., Paul S., Terry A., David T., and Doug K.
(in order of acquaintance).

**My students ...**
...who don't know about closed doors and who are so willing to venture into the unknown. I've learned so much from the amazing ways they make sense of their worlds.

**Someone whose very nature has always inspired me to keep reaching...**
...Rick M. ...who is teaching me how to knock.

# ABSTRACT

The purpose of this study was to investigate how students in Grades Five and Six generate explanations for scientific phenomena and how they evaluate the quality of these explanations. In part, this was done by analyzing the in-class explanations that the students gave in response to questions stemming from two topics in the 1996 Alberta program of studies for Grade Five Science. In addition, the students shared their own perceptions of the sources of their questions and ideas and the methods by which they evaluated them. Analysis of in-class discussions and activities occurred on an ongoing basis between January and June 1998. In addition, five students who vary in their ability to generate and evaluate scientific ideas were selected for more in-depth interviewing outside of class time. These students were interviewed once during each of the main units of study. Their interviews focused on the manner in which their thoughts and ideas had progressed during previous class discussions and activities, how they evaluated these ideas, the manner in which they were able to generate new ideas, and their continued evaluation of these ideas. This involved reflection stimulated by requests to summarize their findings as well as on-the-spot reflection as the students continued to evaluate and develop their ideas. Attention was paid to possible effects that the metacognitive activity encouraged during class discussions and during the interviews may have had on methods that the students used to construct meaning. Each of the students who participated in individual interviews pertaining to specific content areas also participated in a narrative interview that focused on their general interests and habits. The individual interviews and class discussions were fully transcribed, analyzed and compared to generate broad themes which were then able to guide further analysis of student work.

# I. INTRODUCTION

## 1.1. Background and Justification for the Study

In today's society, the need for all students to be able to think scientifically includes a need for basic understanding of scientific concepts, an ability to generate and evaluate scientific arguments, and an understanding of the manner in which scientific knowledge is generated. If students are to support the scientific enterprise and to understand its potential contributions to life on this planet, they need to understand what it entails. To attract capable students to careers that capitalize on their scientific interests and abilities, school science needs to be representative of the broader realm of science and its applications.

As our society becomes increasingly driven by economic urgencies, the importance of pursuing knowledge for its own sake becomes undervalued. According to a study conducted by Abrams and Wandersee (1995), research in science is primarily driven by funding. They attributed this to the "political nature of funding decisions and the public's lack of understanding about the future importance of pure research" and provided several examples of important discoveries that were made as a result of "life scientists' unbridled curiosity about nature" (p. 654). They questioned the impact that funding-driven research has on this sort of discovery. Sagan (1993) presented a similar argument:

> Who discovered that CFCs posed a threat to the ozone layer? Was it the principal manufacturer, the DuPont Corporation, exercising corporate responsibility? Was it the Environmental Protection Agency protecting us? Was it the Department of Defense defending us? No, it was two ivory-tower, white-coated university scientists working on something else -- Sherwood Rowland and Mario Molina of the University of California, Irvine. Not even an Ivy League university. No one instructed them to look for dangers to the environment. They were pursuing fundamental research. They were scientists following their own interests. (pp. 221-222)

Sagan (1996) made an excellent case for all members of society having an understanding of the manner in which science works in *The Demon-Haunted World*. Here he documented the prevalence of pseudo-scientific thinking and expressed fears that such thinking could place tremendous power in the hands of the relatively few who are able to analyze critically scientific information that is presented to them on a daily basis.

The need for all members of society to have an understanding of basic ecological principles is becoming increasingly urgent. As the world's population continues to grow and as consumption levels in developed countries continue to rise, the level of stress we place on our natural environment continues to increase. The effects of unrestrained growth can only be truly understood and appreciated through contrast with the cyclical nature inherent in the chemistry of the natural world.

To attract capable students to scientific fields, the image of science projected by schools must be consistent with its actual practice. In discussing the image of science as a set of facts to be memorized, Carr et al. (1994) made the following claim:

> Although having a good memory is an undeniably valuable attribute there is a good deal of evidence that the memorized knowledge is not well understood. Teaching which values a skill that may not be strongly linked to ability in science can alienate the bulk of students from the discipline before they have properly experienced it. (p. 148)

The same could be said of any approach to teaching science that emphasizes skills or attitudes that differ so markedly from those used by scientists. It seems unlikely that the students who are most likely to excel in science would be attracted to a discipline that emphasizes facts to be memorized and procedures to be followed.

To present school science in a manner that represents more authentic scientific activity, it is necessary to understand both the manner in which science works and the manner in which students are able to think. Through a better understanding of both, pedagogical methods may be better matched with actual scientific practice. In the review of the literature that follows, I attempt to address both of these matters. Much work has been done in an attempt to describe scientific practice, but there are significant gaps between this and much of the work in science education. This study represents one attempt to narrow this gap.

By experiencing and reflecting upon the processes of their own thought within an environment designed to be conducive to scientific thought, the children involved in this study came to better understand the nature of the broader realm of scientific thought and, at the same time, became better scientific thinkers themselves. Understanding how they made sense of their own experiences, their perceptions of the processes involved in doing so, and how these perceptions impacted the ways that they constructed meanings are the primary aims of this study.

## 1.2. The Research Question

How do teacher contributions (e.g. arguments, questions) to scientific discussions / activities in the classroom affect the manner in which students construct scientific ideas?

- What are the sources of students' questions?
- How do students generate ideas about phenomena?
- How do students generate arguments to defend or reject ideas?
- What factors cause students to accept or reject ideas?
- To what extent are students able to monitor consciously and / or to control the manner in which they generate and evaluate their ideas? Is the ability to do so always beneficial?

## 1.3. Definition of Terms

**Accommodation**: the modification of existing knowledge to incorporate new knowledge that in some way conflicts with it (Posner, Strike, Hewson, & Gertzog, 1982)

**Analogy**: a perceived relation between two objects, situations, or processes that differ in one or more ways and between which explanatory structures are transferred

**Analogical reasoning**: the process by which "an explanatory structure is mapped from the source to the target, and its applicability is evaluated on the basis of what is known about the target concept" (Vosniadou, 1989, p. 422)

**Assimilation**: the integration of new knowledge with existing knowledge (Posner et al., 1982)

**Associative leap**: a method of generating analogies that is based upon a perceived similarity between some aspect of the target and base (Clement, 1981)

**Bridging analogy**: a type of analogy generated as an intermediary used to evaluate the validity of the relation between another source analog and the same target; the bridge contains features of the source and target analogs (Clement, 1981)

**Conceptual change**: learning that involves the modification of previously held ideas; this occurs through the process of radical restructuring / accommodation

**Conceptual growth**: learning that involves the addition of new concepts or relations between concepts; this occurs through the process of weak restructuring / assimilation

**Constructivism**: a philosophy of learning in which knowledge is viewed as personally constructed meaning that results from interaction between existing knowledge and new experience

**Constructivist learning**: learning that takes place as a result of interaction between existing knowledge and new experience

**Constructivist teaching**: a method of instruction in which the teacher deliberately addresses the fundamental role of interaction between existing knowledge and new experience in an attempt to facilitate learning

**Context of development**: a context within which the teaching of science may be approached that emphasizes the development of an understanding of the manner in which earlier theories have impacted current scientific understanding (Duschl, Hamilton, & Grandy, 1992)

**Context of justification**: an "ahistorical" context within which the teaching of science may be approached; it emphasizes the development of an understanding of the evidence used to support current scientific theories "without regard to predecessor theories" (Duschl et al., 1992, p. 28)

**Discrepancy**: conflict between new information and existing knowledge

**Elemental physical intuition:** "... 'direct' knowledge of the behavior of a physical object or system – knowledge that does not depend on a formal symbol system"; "abstractions with a certain degree of generality" that "assimilate a certain range of other representations such as members of a certain class of perceived objects" (Clement, 1994, p. 213)

**Epistemological relativism:** stage of understanding the nature of knowledge at which "the possibility of rationally comparing and testing theories is rejected" (Moshman & Lukin, 1989, p. 188)

**External variable:** a variable that may be shown to affect a phenomenon but that has no hypothesized or demonstrated causal role in that phenomenon

**Extreme-case reasoning**: mental manipulation of a situation in which features of a problem or theory are mentally altered to extreme degrees to test the implications of a theory in a manner that makes them more obvious

**Free exploration:** activity that is uninhibited by the need to have an identified purpose

**Generative transformation**: method of generating analogies in which some aspect of a problem or theory is modified to create a more familiar situation that can then be analyzed (Clement, 1981, p. 139)

**Imagistic modeling**: a type of analogy that involves the mental construction of a physical representation of what are believed by the learner to be the salient features of the phenomenon being investigated

**Imagistic simulation**: "...where a schema assimilates a mental image of a particular situation and operates in 'dry run' mode to produce expectations about its behavior" (Clement, 1994, p. 209); a thought experiment that utilizes dynamic imagery

**Implicit mental model**: a generalized explanatory structure that drives a sense of knowing that may be articulated by reference to specific examples that may comprise it; an elemental physical intuition is one type of implicit mental model

**Internal variable:** a variable with a hypothesized or demonstrated causal role in the phenomenon being investigated

**Isolated-case reasoning:** reasoning that occurs when the thinker fails to consider the applicability of a particular theory to other contexts or to variations of the context in which it was proposed

**Knowledge problematic:** a view of knowledge in which "reality exists, but our knowledge of it is elusive and uncertain. Theories are judged to be more or less useful, not strictly right or wrong" (Carey & Smith, 1995, p. 54)

**Knowledge unproblematic:** a view of knowledge in which "there is only one objective reality that is knowable in a straightforward way by making observations" (Carey & Smith, 1995, p. 54)

**Learner-generated analogy**: a type of analogy generated by the person attempting to construct meaningful understanding of a given situation (as opposed to a teacher-generated analogy); Clement (1989a) refers to learner-generated analogies as "spontaneous analogies" (p. 304)

**Metacognition**: awareness and control over one's ideas, thought processes, and beliefs about the nature of scientific knowledge and learning (Gunstone, 1994)

**Misconception**: an idea that is not consistent with currently accepted scientific knowledge

**Negative analogy:** components of a source and target analog that do not correspond to one another (Hardwicke, 1995)

**Neutral analogy:** "grey area consisting of aspects of the source [analog] that are not definitely positive or negative" (Hardwicke, 1995, p. 278)

**Normal science**: scientific activity characterized by its dependence on "one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice" (T. Kuhn, 1970, p. 10)

**Positive analogy:** components of a source and target analog that correspond to one another (Hardwicke, 1995)

**Pre-paradigmatic science**: scientific activity generated in the absence of the guiding set of rules and understandings that characterizes normal science; it is "marked by frequent and deep debates over legitimate methods, problems, and standards of solution, though these serve rather to define schools than to produce agreement." (T. Kuhn, 1970, pp. 47-48)

**Proxy abstraction:** a poorly understood construct used as a substitute for a more complete explanation

**Radical restructuring**: changes in knowledge structures that involve the modification of existing ideas (Vosniadou & Brewer, 1987)

**Reflective abstraction:** a process whereby an individual "constructs a new level of understanding that explicitly knows the previous level and thus creates new knowledge via differentiation and coordination of what was only implicit in his or her interactions with the environment. This new level of understanding, however, itself includes knowledge that can become the object of explicit awareness, thus setting the stage (so to speak) for the construction of a still higher level" (Moshman & Lukin, 1989, p. 195)

**Revolutionary science**: science characterized by the rejection of the ideas upon which normal science in a given field of study is based; it involves the fundamental reorganization and re-evaluation of existing ideas (T. Kuhn, 1970)

**Process skills**: skills required for the empirical investigation of phenomena

**Real science**: method of science employed by practicing scientists

**School science**: method of science defined by school curricula

**Scientific inquiry**: scientific activity involving the generation and evaluation of scientific theories for the sake of generating knowledge and understanding

**Scientific thinking**: the thought processes involved in the generation and evaluation of theories that attempt to explain the processes that constrain the behavior of living and non-living things

**Specific theory**: a theory in which a phenomenon is explained by reference to the roles of salient variables

**Teacher-generated analogy:** an analogy presented by a teacher, textbook, or other external authority in an attempt to help students develop understanding of a particular phenomenon

**Theory:** a set of interrelated ideas that explain the processes constraining the behavior of living and / or non-living things

**Theory evaluation:** various means by which the accuracy of a given theory is judged

**Theory generation:** the connecting and / or reorganization of existing ideas to explain the processes constraining the behavior of living and non-living things

**Theory-in-action:** "the implicit ideas of changing modes of representation underlying the sequences" of "spontaneous organizing activity in goal-oriented tasks" (Karmiloff-Smith & Inhelder, 1975, p. 196)

**Thought experiment:** mental manipulation of objects in a manner that allows the experimenter to explore the implications of a particular theory

**Vague theory:** a theory in which certain variables are identified as potential causal factors but that does not demonstrate how those variables might interact with other elements deemed salient to the phenomenon being explained

**Weak restructuring:** change in knowledge structures resulting from the accumulation of new information and from the creation of new links between already-existing information (Vosniadou & Brewer, 1987)

## 1.4. Hypotheses

$H_0$1: The methods by which students generate and evaluate their ideas are of a qualitatively different nature than the methods used by practicing scientists.

$H_0$2: Student reflection upon the manner in which they generate and evaluate ideas has little or no effect upon the subsequent manner in which they do so.

$H_0$3: Student interests and experiences (in areas other than those being explicitly studied) have, at best, a superficial impact upon the manner in which they generate and evaluate ideas regarding electrical circuits.

$H_0$4: Student interests and experiences (in areas other than those being explicitly studied) have, at best, a superficial impact upon the manner in which they generate and evaluate ideas regarding the interactions between various chemicals.

$H_0$5: Teacher contributions to class discussion do little to foster the development in students of conscious strategies to generate and evaluate scientific ideas.

## 1.5. Limitations

1. The study involved twelve students comprising an existing Grade Five / Six class.

2. The science content which formed the context for this study was based on the Grade Five objectives outlined in the 1996 Alberta Program of Studies for Elementary Science.

## 1.6. Delimitations

1. Throughout the study, it was important to ensure that the classroom provided a meaningful context that was conducive to scientific thought. The initial context employed was based on a review of current literature regarding what scientific thinking entails and what educational contexts have been shown to be most conducive to its practice. The nature of this context is outlined in detail in Chapter Two. As the students reflected upon the manner in which they generated and evaluated ideas, changes were made to this context. These are outlined in Section 4.2: "The Evolution of an Effective Classroom Context."
2. Access to students' thoughts, reflections on their thoughts, and reflections on their thought processes were critical to this study. This information was gathered using the data collection procedures outlined in Chapter Three.
3. In addition to information gathered during class discussions, the study involved the collection of detailed information generated by the in-depth interviewing of five class members of varying ability. The selection of these students was limited by the number of students who volunteered to take part. Further selection was based upon the researcher's judgments of their performance in the classroom, which were based on the assessment criteria outlined in Chapter Three.

4. Because different types of content may affect the manner in which students generate and evaluate their ideas (Jenkins, 1996), it is important to remain cognizant of the possible influences of this factor. This study is based on two topics from the Grade Five Program of Studies, both of which fall within the realm of physics. Within each of these topics, a broad focus question was used to stimulate discussion and activity:

   a) Classroom Chemistry
      - Why do vinegar and baking soda interact in the manner that they do?

   b) Electricity and Magnetism
      - Why do various circuit arrangements affect the operation of a bulb in the manner that they do?

The development of these questions is outlined in Section .4.2.

White (1994) identified eight factors that may influence the learning of different types of content:

1. the likelihood that most or all students have common perceptions regarding the subject matter through their daily experiences
2. the presence and power of alternative models to explain certain phenomena
3. the use of words which differ in their scientific context and their everyday context
4. the degree of abstraction evident in and the complexity of the subject matter
5. the types of knowledge used; for example, "propositions, images, episodes, strings, procedures, and motor skills" (p. 259)
6. whether the subject matter is empirical (demonstrable) or arbitrary (such as a classification system)

7. the social acceptance and emotive power of the subject matter

8. the degree to which the content is readily linkable to other familiar areas

Throughout this study, it was obvious that the students' individual experiences had a tremendous bearing on the manner in which they interacted with different content areas. Although it was impossible to select content areas to make possible the observation and analysis of the effects of this many content-related variables, remaining aware of their possible impact on the manner in which the students interacted with the ideas within different content areas strengthened the analysis of the collected data.

The nature of basic circuits and the vinegar and baking soda reaction were familiar to all of the students, but primarily on a superficial basis. In attempting to determine reasons for the behavior of these phenomena, abstract theories were needed for both. Alternative models were most prevalent in the students' understanding of electrical circuits, as was evident in the heated debates that took place regarding one-way vs. two-way current. Both units were characterized by the search for empirical understanding rather than arbitrary classifications, and neither had any inherently emotional components. Over the course of the wide variety of investigations undertaken by the students, many different types of knowledge were incorporated into each of the units. In many ways, then, the selected topics were similar. As such, they do not allow consideration of factors such as emotional response, do not provide a context in which the development of abstract concepts may be compared to the development of those that are more concrete, and do not deal with the development of arbitrary classification schemes. They do provide what appears to be a fair arena for examining the existence of thinking strategies within complex, abstract content areas regarding which students have only superficial understanding.

## 1.7. Assumptions

The following assumptions are made in this study:

1. The methods of school science should be modeled as closely as possible on the methods of actual scientific practice.
2. It is possible to describe the manner in which students generate and evaluate scientific ideas.
3. Scientific thinking can be partitioned into learnable component parts.
4. Students in Grades Five and Six are capable of accurate reflection on their thought processes.

# II. A REVIEW OF THE LITERATURE

## 2.1. Introduction

To define an appropriate classroom context in which to conduct this study, it was necessary to explore aspects of the historical, philosophical, epistemological, psychological, and educational roots of scientific thinking. In addition, it was necessary to synthesize the characteristics identified in the literature as important to student thinking with my own prior experiences so that I was able to create a grounded and coherent framework that could guide my initial observations and analysis of student learning. The review of the literature that follows delineates this framework. Clearly, the classroom context impacts the nature of the opportunities that exist for thinking (Gunstone, 1994; Gunstone & Northfield, 1994; Wong, 1996). As my own knowledge and understanding of a productive context for scientific thinking evolved over the course of the study, the context in which it took place was altered in various ways. These are outlined in Section 4.2.

## 2.2. What is Scientific Thought and What is its Role in Science Education?

> *There are, oddly, no technical rules for success in science. There are no rules even for using test tubes which the brilliant experiment does not flout; and alas, there are no rules at all for making successful general inductions. This is not where the study of scientific practice leads us. Instead, the conditions for the practice of science are found to be of another and an unexpected kind. Independence and originality, dissent and freedom and tolerance: such are the first needs of science; and these are the values which, of itself, it demands and forms.*
>
> (Bronowski, 1964, p. 68)

"Thinking scientifically" is a rather nebulous, all-encompassing phrase that does not adequately delineate the framework of this study. School science is often divided into categories pertaining to inquiry or investigation, technology, and decision-making. Furthermore, "the history of school science education is a recurrent cycle of periods in which the *method* of science has been strongly emphasized in curriculum rhetoric, interspersed with periods when content features more prominently" (Millar & Driver, 1987, p. 34). Finally, whether the classroom focus is on content, process, or a combination of the two, what are considered acceptable means of imparting and / or helping students construct knowledge may be located anywhere along a continuum between didactic and heuristic pedagogical frameworks. The complexity of this situation is apparent in D. Roberts' (1983) seven curriculum emphases for science education. Although his categorization represents a very dissected view of science, it is useful in terms of discussing which elements, and in which combination, are critical to the development of scientific thought.

### 2.2.1. Inquiry, technology, and decision-making.

Although the types of thought involved in inquiry, technological, and decision-making contexts are integrally related, each has distinct features. To clarify the intended focus on scientific inquiry, a brief description of the differences between these emphases is necessary.

D. Roberts (1983) included both technology and decision-making in the emphasis he termed "Science, Technology, and Decisions" (p. 12). This emphasis is similar to the description of the "Relationship of Science, Technology, Society, and the Environment" subsection of Foundation 3 in the October 1996 draft of the Pan-Canadian Common Framework of Learning Outcomes K to 12 (Council of Ministers, Canada, 1996, p. 3) in that both focus on the interdependence of science and technology within a given societal context. The explicit focus on the environment is a distinguishing feature of the Pan-

Canadian categorization. D. Roberts' (1983) emphasis on decision-making is addressed in Foundation 4 of the Pan Canadian framework: "Strategies and Skills" (Council of Ministers, Canada, 1996, p. 3). The need to make decisions regarding the appropriate use of science and technology may drive scientific inquiry in that it sometimes requires information that must be sought through scientific investigation. Decision-making is an important component of inquiry, but the decisions involved are not necessarily directed toward a moral or ethical end. Consequently, they have a different goal than inquiry per se. Clearly, it is possible to develop new technologies without considering their societal or environmental implications. Similarly, knowledge may be pursued without consideration of the possible consequences of acquiring that knowledge. Norris' (1992) discussion of areas in which decision-making is an important part of scientific reasoning within the inquiry framework provides a useful contrast. He identified the following ways that decision making is a necessary part of inquiry: (a) choosing standard conditions, (b) deciding that evidence is strong enough to falsify a theory rather than stimulate a change in the theory, and (c) making value judgments regarding the degree of specificity of and manner of solving equations. All of these are part of a search for objective truth rather than for an ethical definition of right or wrong. The societal impact of inquiry and technology is not explicitly addressed as an organizing framework in the 1996 Alberta Program of Studies for Elementary Science. Rather , goals representative of this focus are integrated within the various units.

Within Foundation 3 of the Pan-Canadian framework, distinctions are drawn between the "Nature of Science" and the "Nature of Technology" (Council of Ministers, Canada, 1996, p. 3). The 1996 Alberta Program of Studies for Elementary Science includes ideas relating to "The Nature of Technology" in the units that have been identified as having a "problem solving through technology" emphasis (p. A.3). Like decision-making goals, technological goals may drive scientific inquiry in that they sometimes provide impetuses for the questions that stimulate it. However, their goal is a useful product or technique. Understanding the related principles and processes is often necessary, but the value of such understanding is secondary to the value of the product itself. Ensuring that the ideas used to develop the product are consistent with those of a particular paradigm of scientific understanding is not the primary aim of these types of activity.

The decision to focus this study on science inquiry does not reflect an attempt to isolate it from its integral relationship with technology and society. Instead, it helps to focus on those thought processes that are necessary for the generation and evaluation of ideas. This focus is clarified in the following sections.

### 2.2.2. Process.

According to Millar and Driver (1987), the term "process skill" has taken on several meanings: "the processes scientists use in investigating the natural world; the cognitive processes involved in learning science and the pedagogical processes taking place in classrooms" (p. 39). For purposes of the current discussion, the term "process skills" is consistent with their first definition, whereas cognitive and pedagogical processes are referred to as such. In describing "Scientific Skill Development," (p. 12), D. Roberts (1983) focused on process skills defined in this manner. His description of this framework has much in common with the emphasis of the 1983 Alberta Program of Studies for Elementary Science (Alberta Education). In this document, the importance of the skills of observing, classifying, measuring, and communicating are emphasized for Division I, and the presumably more advanced skills of inferring, predicting, controlling variables, interpreting data, defining operationally, hypothesizing, formulating models, and designing experiments form the focus for Division II. Such skills are undoubtedly important. However, when they are divorced from the theoretical frameworks that lead to the questions necessitating their use, their use becomes little more than decontextualized drill that does not emphasize how scientific knowledge develops and does not give children the opportunity to form the problems and hypotheses which are at the heart of meaningful experimentation. It does not make sense to observe, classify, and measure in the absence of a theoretical framework when such activities are themselves theory-dependent (Hodson, 1996; T. Kuhn, 1970; Millar & Driver, 1987). Even young children are able to infer, predict, hypothesize, and control variables when the questions they are investigating are grounded in their own theories and knowledge structures.

Process skills may be seen as part of a broader integrated framework that does not allow them to function as discrete components. Munby (1982) emphasized these concerns in his discussion paper of scientific thinking:

> ...Quite frankly, I find the "scientific method" very tiresome. First, the history of science shows that the scientific method does not seem to lead to mind-boggling conceptual novelties. (In fact, we are likely forced to describe such "discoveries" according to a logical step-wise progression simply because it is far easier to follow a tale when it is told like that....) (p. 30)

### 2.2.3. Content.

When content is dealt with in a manner that ignores the processes by which knowledge is constructed, as in D. Roberts' (1983) "Correct Explanations" (p. 12) emphasis, it must rely heavily on rote memorization and emphasizes the products rather than the processes of science. As is noted in the discussion of student misconceptions and conceptual change in Section 2.3, such an approach does not effectively alter students' misconceptions

(Posner et al., 1982) and results in "inert knowledge" (Whitehead, 1929). In addition, views of science that rely on memorization of bodies of knowledge do not teach students to think like scientists and do not teach them to appreciate the dynamic nature of scientific knowledge, with the "tortuous history of its great discoveries and the misapprehensions and occasional stubborn refusal by its practitioners to change course" (Sagan, 1996, p. 22). However, these criticisms in no way undermine the importance of content to scientific thinking.

### 2.2.4. Uniting content, process skills, and thinking processes.

> *There is no way to tell whether the patterns extracted by the right hemisphere are real or imagined without subjecting them to left-hemisphere scrutiny. On the other hand, mere critical thinking, without creative and intuitive insights, without the search for new patterns, is sterile and doomed. To solve complex problems in changing circumstances requires the activity of both cerebral hemispheres: the path to the future lies through the corpus callosum."*
>
> (Sagan, 1977, pp. 190-191)

Although approaches to science education that are strictly content oriented may not reflect scientific thought, content is vitally important to thinking scientifically, and an understanding of the manner in which scientific knowledge develops is important to this process. Whereas the development of traditional process skills may be viewed as drill when performed in a theoretical vacuum, these skills form a critical part of scientific thought in that they aid in the gathering the information necessary to evaluate and / or build upon a given theory. However, there are other important ways that this takes place. Information based upon the ideas of others and from one's own background knowledge and experiences are also critical to theory evaluation. The nature of the development of science, or what D. Roberts (1983) called "Structure of Science," exemplifies this idea:

> A "Structure of Science" emphasis orients teaching in such a way that the student comes to understand how science functions as an intellectual enterprise. Attention is given to the relationship between evidence and theory, the adequacy of any given model to explain the phenomena at hand, the self-correcting features of the growth of science, and similar matters relating to the way in which scientific knowledge is developed. (p. 12)

Clearly, such an understanding cannot be adequately developed without reference to content, nor can the necessary evidence be gathered without skill in processes such as developing fair tests and devising and / or using accurate systems of measurement. In addition, the thinking processes involved in generating and evaluating ideas are critical to the development of understanding. Content, process skills, and thinking skills must work interdependently to facilitate an understanding of "The Structure of Science":

> An important outcome of this lively debate about the content for school science has been the recognition that polarized solutions...are no solution at all. While consideration of topics leads to different conclusions from those derived from consideration of emphases, these and other aspects of science are not discrete. They interact with each other. The measuring instruments scientists use embody conceptual relations established in earlier stages of scientific enquiry. Observations are not independent of criteria that stem from categories for conceptualizing the phenomenon being observed. (Fensham, Gunstone, & White, 1994, p. 2)

Carey, Evans, Honda, Jay, and Unger (1989) expressed a similar notion:

> Certainly, process skills are important elements of careful scientific methodology. Junior high school students do not spontaneously measure and control variables or systematically record data when they first attempt experimental work. Yet, the standard curriculum fails to address the motivation or justification for using these skills in constructing scientific knowledge. Students are not challenged to utilize these process skills in exploring, developing and evaluating their own ideas about natural phenomena. Rather, instruction in the skills and methods of science is conceived as being outside the context of genuine inquiry. Thus, there is no context for addressing the nature and purpose of scientific inquiry, or the nature of scientific knowledge. (pp. 514-515)

The views of these authors are consistent with the "science inquiry" approach described in the 1996 Alberta Program of Studies for Elementary Science (p. A.3) and with the "Nature of

Science" designation outlined in the 1996 Pan-Canadian framework (Council of Ministers, Canada, 1996, p. 3). Students are expected to focus not only on problem solving using the skills emphasized in the "Scientific Skills Development" framework, but also on problem finding. The skills are important, but only in solving real problems:

> An inquiry may be initiated in a variety of ways. It may be based on a question brought to the classroom by a teacher or student, or it may arise out of an activity, an interesting observation, an unexplained event or a pattern that appears worth pursuing. Engagement in inquiry is not a linear process. It can have a variety of starting points, and the steps followed may vary from one inquiry activity to another. When an unexpected observation is made or a procedure does not work, there is opportunity for new ideas to emerge and a new set of procedures to be followed. (D. Roberts, 1983, p. A.3)

It is within this guiding framework that this study is set. It is the interdependence of evolving content with thinking processes and process skills in the pursuit of scientific truth that exemplifies scientific inquiry.

### 2.2.5. Real science vs. school science.

Some researchers have questioned the value of approaching science education with a rationale based on the way scientists work (Caravita & Halldén, 1994; Hodson, 1996; Millar & Driver, 1987; J. Osborne, 1996). They criticize the manner in which the parallels between the development of students' ideas and the development of scientific ideas over the course of history have sometimes been improperly used to equate students' science with scientists' science. Duschl et al. (1992) presented a view of science education as a choice between a context of justification and a context of development, neither of which adequately address legitimate scientific activity in the classroom. Wong (1996) and Caravita and Halldén (1994) attempted to draw distinctions between students and scientists on numerous grounds. Many of their arguments underestimate the sophistication of the ideas and arguments that students are able to generate.

In their comparison of the merits of context of justification and context of development approaches to science education, Duschl et al. (1992) defined a context of justification as a method of teaching science in which students either generate or are taught evidence for existing theories, and a context of development approach as one in which students are expected to understand the historical development of the ideas that they are studying. However, these are not the only alternatives. Understanding the nature of science is an important goal. However, children are more likely to gain an understanding of this process if they reflect on their own contexts of development, which will not always mirror those of the historical development of those ideas. Students today are surrounded with evidence of scientific principles in action through their interactions with current technology and their participation in the society in which they live. Although they may not have a clear conceptual understanding of the scientific principles-in-action that surround them, their perceptions of the operation and effects of devices and techniques not known to early scientists and their daily interactions in a relatively advanced society cannot help but impact the manner in which they interpret various phenomena. It seems likely that students could gain a better appreciation of the "false starts and misdirections" (Duschl et al., 1992, p. 36) of science if they actually experienced them than they would by participating in a re-creation of those experienced by scientists in history. This is not to say that students should not learn about the historical development of ideas, but suggests that such accounts would likely make more sense with personal experience to illuminate them. Carey et al. (1989) expressed this sentiment in their rationale for a unit of study intended to help students gain knowledge, skills, and an appreciation of the nature of science:

> We assume that process skills will be more easily and better learned if they are embedded in a wider context of metaconceptual points about the nature of scientific knowledge. We also assume that such knowledge is important in its own right, and that it can be gained only by actively constructing such knowledge and reflecting on this process. These assumptions motivate a curricular approach that emphasizes theory building and reflection on the theory building process. (p. 517)

In fact, when the context of development is considered in terms of the students' own development, presenting evidence for currently held theories could be considered part of both the contexts of development and justification. If ideas were presented at a time when they could meaningfully interact with students' conceptions, the students could construct meaning that is both consistent with current theory and based on a developmental process. This idea is further developed in Section 4.4.4.

Emphasizing the importance of a context of development in terms of the students' development need not undermine the valuable role that lessons from the historical record may play in furthering children's understanding. As Posner et al. (1982) claimed, "retrospective anomalies" (p. 225) may serve as effective sources of discrepant events by which children's ideas may be more effectively challenged. However, they need not be presented in the manner that they occurred during history. Teachers today have the advantage of hindsight and are thus able to provide students with arguments and demonstrations that the scientists working at the time of initial theory developments did not have. Taking advantage of hindsight does not make classroom activity less scientific. Argument and counterexamples were important contributors to the development of scientific knowledge, and the historical record provides us with a rich store of ideas with which misconceptions may be countered. As Nersessian (1992b) claimed in her "cognitive-historical" model, "the history of science should be viewed as *a repository of knowledge of how to go about constructing, changing, and communicating scientific representations* [italics in original]" (p. 54).

Sometimes students may gather necessary information through experiments of their own design, but this need not always be the case for classroom activity to be termed scientific. It is true that students do not and cannot always have access to the resources necessary to replicate the experiments of others or to collect the data they have identified as necessary (Wong, 1996). Even if time were not a complicating factor, they may have little choice but to accept some information at face value. However, if such information is consistent with or can be reconciled with their current ideas, this need not implicate irrational or non-scientific activity. The students in this study spent a great deal of time arguing about the implications of both empirical results and other background knowledge, which often included information that they had previously heard about, read about, or otherwise obtained from external sources. As is demonstrated in Chapter Four, such discussion is critical in terms of helping the students connect new experiences to their own understandings.

Caravita and Halldén (1994) claimed that students are incapable of experimenting for the purpose of seeking and interpreting evidence. In their view, students' "main objective is to optimize a desired outcome" (p. 93). As is very evident in the transcriptions of student dialogue provided by Cosgrove (1995) and Segal and Cosgrove (1995), many students are very capable of moving beyond experimentation that is based on optimizing desired outcomes. Goal-directed activity was certainly evident in the self-chosen activities in which the students participating in this study engaged, but some students moved well beyond this type of activity. This is clearly shown in Section 4.3.1.

Wong (1996) questioned the ethics involved in requiring students to provide deeper and deeper levels of explanations:

> My predictable request for them to say more or explain further may have created the impression that *no* level of explanation was, in fact, acceptable to me. The criteria for success in my class thus had less to do with providing a particular response than with the spirit and intention to construct ideas that were progressively more sophisticated. Admittedly, such teacher expectations are unorthodox, and with the benefit of hindsight, I see that participating in my class must have been an unsettling experience for some students. (p. 503)

As students gain an appreciation of the idea that the goal of science is a search for truth rather than a search for solutions, however, they become very concerned with the sources and nature of the evidence that they collect. In addition, as they become accustomed to the idea that they are being evaluated on the basis of the depth of their thought rather than on correct answers or definitive proof, their discomfort with such methods begins to dissipate. As in any situation, providing positive reinforcement and encouragement for desired behaviors can reassure students that what is requested is indeed possible. In Section 4.2, there is evidence of the frustration experienced by many of the students in this study as they tried to come to terms with the point of seeking deeper and deeper levels of why. Later, in Sections 4.3.1.4 and 4.3.3.2.3, Carl's vexation with his emerging realization that he might never obtain definitive answers for his questions also displays the type of frustration that such activity may elicit. Rather than viewing this as a problem, however, it may be viewed as an important stage in students' development of a more accurate understanding of the nature of science and knowledge.

In similar arguments, Caravita and Halldén (1994), Millar (1989), and Wong (1996) emphasized the fact that when the teacher already knows what are perceived as the correct answers, students are less motivated to develop and evaluate their own explanations. However, if students are given reinforcement for developing and evaluating ideas rather than solely for developing ideas that are consistent with current scientific knowledge, they become motivated to do so. This is not intended to promote a relativistic view of science. Through further argument and refinement of these ideas, students can be expected to develop an understanding of concepts that is consistent with currently accepted knowledge. The end product need not be the only thing that is valued for this to happen. Once students realize that answers are not all that matters, they become less impatient to arrive at these answers. When their ideas and arguments are truly valued, students are willing to work at the development, evaluation, and modification of their ideas. This is very evident in the segments of dialogue presented in various contexts throughout Chapter Four.

Both Caravita and Halldén (1994) and Wong (1996) drew a distinction between the nature of peer interaction in a community of scientists and that in a community of students. Caravita and Halldén (1994) claimed that

> interest in and attention to what others have to say is a habit acquired through situations where there are shared goals, recognized distributed expertise, credibility to be gained, need of the others' support, different legitimate modalities for communication, and a group identity. It is hard to believe that these are conditions one will readily find in the science classroom. (p. 93)

The features of scientific interaction set out by Caravita and Halldén (1994), although they may not be readily found in science classrooms, can certainly be fostered. Evidence of students' ability to operate within and to take an active role in the construction of such a classroom context is detailed in Sections 4.2 and 4.3.5. Students' motivations to participate in this type of activity range from a desire to please the teacher and achieve good grades (when they know that these features are being evaluated) to a genuine desire to explore and develop new ideas for their own sake. Regardless of their motivations, students can develop a deep appreciation of the contributions that dissenting opinions can play in moving toward truth.

Wong (1996) described his concerns with the nature of peer interaction among students in a science classroom as follows:

> In scientific communities, differences among explanations are a critical impetus for scientific inquiry and discussion. However, my middle school students simply shrugged their shoulders and seemed quite comfortable with the fact that different people had different ideas. (p. 504)

The understanding of the importance of argument is also something that can be learned. As children learn to distinguish between quarrelling and arguing, they learn not to take disagreements personally and begin to engage much more freely in debate. In fact, they love to argue. The classroom environments and interactions evident in recent studies by Cosgrove (1995) and Segal and Cosgrove (1995) provide ample evidence of this notion, as do many of the dialogues presented in Chapter Four. In fact, many of the students make explicit reference to the ways in which argument helps them to develop their ideas. This understanding forms an essential component of the developmental progression for communication skills, which is described in Section 4.3.5.

When the importance of a classroom context in which students act like a community of scientists is emphasized, an examination of the constructivist / conceptual change view of learning becomes necessary. In many ways, this view provides a context in which D.

Roberts' (1983) "Structure of Science" (p. 12) approach to science education may be exercised. Strike and Posner's (1992, p. 171) "persistent attention to the argument" seems to be at the heart of both real and school science:

> Perhaps what conceptual change theory requires is fewer teachers who emphasize calculating the right answer in their tests and instruction, and more teachers who emphasize the connections between physical conceptions, experimental evidence, and students' current conceptual ecology. If conceptual change theory suggests anything about instruction, it is that the handles to effective instruction are to be found in persistent attention to the argument and in less attention to right answers. Better to act as though the world is rational than to produce homilies on the theme. (p. 171)

## 2.3. Constructivism and Conceptual Change

There is a large and growing body of literature in the field of science education that deals with the prevalence and the tenacity of children's (and adults') misconceptions of scientific phenomena (Alberta Education, 1996; Driver, 1989; Gardner, 1991; Kass, 1992; Posner et al., 1982). Gilbert and Swift (1985) referred to this shift in emphasis as the "Alternative Conceptions Movement" (p. 682). Closely related to this movement has been the development of a constructivist model of learning (Driver, 1989; Millar, 1989; Posner et al., 1982; Treagust, Duit, & Fraser, 1996), which emphasizes the manner in which all learning must involve the active construction of knowledge. Millar (1989) explained the relationship between a constructivist model of learning and the nature of conceptual change as follows:

> . . . These ideas lead to a constructivist model of science learning, in which concept change is seen as the product of interaction between existing conceptions and new experiences. A valuable insight from this model is that concept learning is understood as a *reconstruction of meaning* rather than simply the *accretion* of new ideas; this in turn may go some way towards explaining why promoting conceptual change is so difficult [italics in original]. (p. 588)

According to the constructivist view of knowledge and learning, human perception of the world is subjective. Our observations are dependent upon the theories that drive them. Learning is viewed as the construction of meaning that results from interactions between our previous knowledge and what we experience in the world around us (Carr et al., 1994). New concepts are either assimilated, whereby they are considered unproblematic by the learner and may co-exist with previous ideas, or accommodated, whereby they are perceived as incompatible with current knowledge and stimulate the alteration of existing ideas that is conceptual change (Posner et al., 1982). Vosniadou and Brewer (1987) referred to the changes in knowledge structures that result from assimilation as weak restructuring and those that are due to accommodation as radical restructuring. Radical restructuring may involve deeply entrenched ideas upon which many other understandings are built, or it may involve ideas that may be changed without effecting significant impact on other knowledge structures. T. Kuhn (1970) referred to conceptual change involving well-entrenched ideas as revolutionary science. He contrasted this with both the conceptual growth that involves the assimilation of new ideas and with the accommodation of ideas that do not affect well-entrenched ideas. He included both of these in his description of normal science, and referred to conceptual change in this type of non-revolutionary context as "puzzle-solving" (p. 35).

It is important to emphasize that the consistency or inconsistency of a given piece of information cannot be judged by its degree of consistency with accepted scientific theory. It must be viewed in light of the learner's perception of its relationship to his or her prior knowledge. This distinction has led to considerable debate regarding the use of the term "misconception" in reference to ideas that are inconsistent with those generally accepted by the scientific community. Some have argued that its use wrongly implies faulty reasoning on the part of the student. Others have countered this with the argument that substituting terms like "prior conceptions" (Driver, Asoko, Leach, Mortimer, & Scott, 1994) or "alternate conceptions"

(Gilbert & Swift, 1985) lends false credence to students' ideas and promotes scientific relativism (Hodson, 1996). Although the implication of relativism by the use of these terms is far from obvious, the term "misconception" is used throughout this discussion for the sake of clarity and consistency.

Both students and teachers need to recognize that certain ideas are unsupported by current evidence. This need not imply that they lack value. When students' prior conceptions are taken into account, there are instances when misconceptions may be deemed more logical than scientifically accepted conceptions. For example, most students beginning their studies of simple DC circuits believe that such circuits are comprised of either clashing current from the positive and negative terminals of a battery or of current that is used up as it passes through various resistances in the circuit (R. Osborne, 1983; Shipstone, 1984). The view of a simple series circuit as one in which there is a constant amount of current in all parts of the circuit is very difficult to visualize without some understanding of what is moving and what is causing the motion. Shipstone (1984) provided evidence that the idea of current being used up actually increases in prevalence between the ages of twelve and fourteen, and claimed that

> there is evidence that it is the more able pupils who develop the sequence model most rapidly. Some in the first two years who did not apply the sequence model [which he uses to describe the notion of current being used up as it passes through the circuit] to question 2 [which questioned the students on the brightness of a bulb located between two resistors in a series circuit when each of the resistances was increased or decreased], answered correctly but many had no consistent way of answering the four parts of this question. (p. 192)

Misconceptions often form the basis upon which further concept development must take place. According to T. Kuhn (1970):

> Without commitment to a paradigm there could be no normal science. Furthermore, that commitment must extend to areas and to degrees of precision for which there is no full precedent. If it did not, the paradigm could provide no puzzles that had not already been solved. Besides, it is not only normal science

> that depends upon commitment to a paradigm. If existing theory binds the scientist only with respect to existing applications, then there can be no surprises, anomalies, or crises. (pp. 101-102)

Students' misconceptions must be at the heart of their normal science if it is to make sense to them. It was important to monitor the processes by which the students involved in this study came to recognize that certain ideas are not supported by current evidence and subsequently constructed new representations. These processes are discussed in various sections of Chapter Four.

A similar debate exists with regard to reference to children's ideas as "theories." Some contend that "theory" implies a much more integrated and well-thought-out body of knowledge than that which they feel exemplifies children's ideas regarding most or all bodies of scientific content (di Sessa, 1983, 1988). However, this may be viewed as a difference in degree rather than of kind. Although some may be better developed than others, all ideas that have been evaluated are theories. Children's theories may be nascent and amenable to change or well-entrenched and very difficult to change. According to the definition used here, they are still theories. Vosniadou's (1994) comments support this idea:

> . . . the main difference between the novice and the expert is *not* that the novice's physical knowledge is in pieces and the expert's tied to physical laws and principles, but that the novice's knowledge is tied to ontological and epistemological presuppositions that provide a radically different explanatory framework to fundamentally similar experiential beliefs than the principles and laws of physics. (p. 64)

Children build their understandings on the basis of theories such as these, and they form the basis of a context in which they can learn the processes of science. This is equally true of theories that are based on the adequate-so-far-with-the-current-evidence of children and of those that are based on the adequate-so-far-with-the-current-evidence of scientists. As students progress in their understanding of a particular topic, they move closer to current scientific understanding of the phenomenon being studied. In so doing, they may gain a deeper understanding of the nature of the knowledge they have acquired and the nature of the thought processes that made such development possible. Evidence of the development of such understanding is presented throughout Chapter Four.

### 2.3.1. Constructivist models of teaching.

Several authors have cautioned against the automatic equating of a constructivist model of learning with a constructivist model of teaching (Millar, 1989; Strike & Posner, 1992; Treagust et. al., 1996). Treagust et al. (1996) emphasized the idea that "students actively construct their own knowledge whenever they learn something" (p. 5). As Millar (1989) pointed out, "most of us who think we 'understand' some science concepts did not arrive at this understanding by experiencing teaching programmes structured on constructivist lines" (p. 589). However, both Millar (1989) and Treagust et al. (1996) acknowledged the likelihood that they would have constructed a great deal more knowledge if they had. According to Fensham et al. (1994), "Good learning incorporates linking, and good teaching promotes it. Even better learning follows when students comprehend why links are important, and actively seek them for themselves between topics and across subjects" (p. 7). Millar (1989) suggested that perhaps "science should be taught in whatever way is most likely to engage the active involvement of learning, as this is most likely to make them [the students] feel willing to take on the serious intellectual work of reconstructing meaning" (p. 589). Motivation is, of course, a critical element of constructivist learning, and as such, should be part of any constructivist model of teaching. In itself, however, being motivated will likely not be sufficient cause for students to recognize and subsequently modify their misconceptions.

Constructivist ideas are becoming very common in teaching methods that attempt to promote conceptual change: "Conceptual change, as we currently conceive it, involves the learner recognizing his / her existing ideas and beliefs, evaluating these ideas and beliefs (preferably in terms of what is to be learned and how this is to be learned), and then personally deciding whether or not to reconstruct these existing ideas and beliefs" (Gunstone, 1994, p. 132). This description of conceptual change is very similar to Hodson's (1996) description of the main tenets of constructivist teaching:

1. Identify students' ideas and views.
2. Create opportunities for students to explore their ideas and test their robustness in explaining phenomena, accounting for events and making predictions.
3. Provide stimuli for students to develop, modify and, where necessary, change their ideas and views.
4. Support their attempts to re-think and reconstruct their ideas and views. (p. 127)

The first step in each of these frameworks emphasizes the need for students to reify their understandings. This type of metacognition is discussed more fully in Section 2.5. Approaches such as these have often emphasized the importance of discrepant events (Friedl, 1972; Liem, 1987), peer interaction (Carr et al., 1994; Champagne, Gunstone, & Klopfer, 1985; R. Kitchener, 1992), and Socratic questioning (R. Kitchener, 1992; Posner et al., 1982) as impetuses for students to change their ideas. The themes identified as important in Section 4.4 directly support the notion of teaching for conceptual change.

Some might argue that the direct sharing of information and procedures, which is also identified as a vital teacher role, goes beyond or is inconsistent with the ideas that such a conceptual-change model would deem appropriate. Millar (1989) suggested that constructivist instructional styles may be more appropriate for some concepts than for others.

However, making a conscious choice to employ a method of teaching that directly confronts student misconceptions or that provides or facilitates access to information that may be more easily assimilated (as opposed to accommodated) is itself a decision that reflects a constructivist model of instruction. There is no reason why such a model should require teachers to deal with misconceptions where none exist. Conceptual change may be effectively approached with a constructivist model of instruction, but so may other types of learning.

Part of the confusion between constructivist teaching and learning seems to arise in the common association of constructivist teaching with pedagogic methods that reject didactic sources of knowledge. As Strike and Posner (1992) pointed out, conceptual change models of teaching that rely on constructivist philosophies are not partial to a particular method of imparting information. These ideas need not be limited to teaching for conceptual change. They are equally applicable when the information to be learned involves conceptual growth.

Regardless of the means of imparting and / or facilitating access to information, the importance of social interaction in processing information is fundamental to constructivist philosophy:

> Such claims, however, become arguments for discovery learning (where discovery learning is seen as the opposite of direct instruction) only if one assumes that evidence for or against various ideas cannot be communicated verbally. We see no reason to make any such general assumption. Indeed, it seems obvious to the point of requiring no argument, that a great deal of inquiry involves much talk. Explaining, arguing, constructing metaphors, giving counter examples, and the like express the social character of rationality. Views that assume that people are being rational only when they discover things for themselves (where discovering is somehow juxtaposed to being told about) strike us as so wrongheaded as to require some inquiry into why people should believe them. (Strike & Posner, 1992, p. 170)

Carr et al. (1994) further emphasized the importance of the social nature of knowledge construction:

> The most important feature of an approach to science classes which addresses the difficulty of changing ideas is *conversation*. Science lessons which continually seek learners' ideas, which help to clarify them, and which provide an open and unthreatening environment for changing these ideas through conversation are classes in which learning in science can be improved. The false idea that science is exact and therefore that concepts in science are unproblematic can be argued to have trapped science teaching into a pedagogy which misrepresents both the content of science and the process whereby this content is constructed. (p. 158)

How information is introduced to students is not at issue. It is what the children do with the information that needs to be carefully considered. Whether a teacher, parent, or classmate presents a piece of information or the student discovers it independently is not relevant: "All learning involves construction of meaning, whether the knowledge is discovered or received by direct transmission" (Fensham et al., 1994).

A related concern is inherent in the idea that if children are "doing hands-on science," they must be learning. According to Nersessian (1992b),

> The predominant ideology among science educators is that hands-on experience is at the heart of science learning. This ideology arises from the erroneous assumption that scientific method involves primarily induction from data. It also fails to take into account the real possibility that students will simply assimilate the new 'data' to their pre-existing conceptualizations. (p. 66)

Again, it is not the source of the information that is at issue. More important is whether the information that is being presented is grounded in the child's theoretical framework in a way that allows it to either be integrated or to come into conflict with his or her current ideas. The fundamental role of argument, both with self and others, is evident throughout Chapter Four. Empirical investigation provided important information to support these arguments, but many of the arguments were based on the students' experiences and interactions outside of the classroom.

## 2.4. Concerns with Constructivist Teaching Models

*Both skepticism and wonder are skills that need honing and practice. Their harmonious marriage within the mind of every schoolchild ought to be a principal goal of public education. I'd love to see such a domestic felicity portrayed in the media, television especially: a community of people really working the mix – full of wonder, generously open to every notion, dismissing nothing except for good reason, but at the same time, and as second nature, demanding stringent standards of evidence – and these standards applied with at least as much rigor to what they hold dear as to what they are tempted to reject with impunity.*

(Sagan, 1996, p. 306)

Although the constructivist model of teaching described in the previous section provides a context in which the development of scientific thought may take place, it needs to be extended. It has been criticized for its lack of attention to several factors. First, the creation of dissonance by means of argument, through the presentation of discrepant events, or by any other means does not guarantee that students will be motivated to reconstruct their ideas (Caravita & Halldén, 1994). Second, not all new knowledge requires modification of existing ideas. Constructivist teaching models do not always consider the manner in which the development of new knowledge takes place when conceptual change is not the issue (Gunstone, 1994). A third concern involves the idea that children do not always have well-formed ideas that may be elicited and subsequently challenged and modified (White, 1994). Finally, constructivist teaching methods have been criticized for their lack of attention to the manner in which children evaluate both existing and new ideas and to the manner in which students develop new ideas to replace those that have been shown to be discrepant (Driver, 1989; Millar, 1989; Nersessian, 1992b; Wittrock, 1994).

### 2.4.1. So what if an idea "doesn't fit"?

According to Caravita and Halldén (1994), "Establishing cognitive conflicts is . . . a problematic enterprise because students often apprehend counterexamples to their established views as mere anomalies or as being explainable by ad hoc hypothesis" and "individuals often seem able to bear conflicts quite well" (p. 95). It seems that the perceived lack of motivation associated with students who do not appear to experience the expected dissonance anticipated in response to a particular argument or discrepant event may be due, at least in part, to the students' failures to perceive the alleged discrepancies. If so, the problem lies with the argument, not the student, and accentuates the need for a different argument. As Gunstone (1994) asserted, "What is significant here is that it is the individual for whom we seek conceptual change who must be dissatisfied, and who must see fruitfulness in the new conception. That is, the achievement of dissatisfaction and fruitfulness depends on the learner" (p. 133). Vosniadou (1994) expressed a similar conviction:

> Many researchers assume that students are internally inconsistent if they use a scientific concept correctly in some cases but not in others. The possibility that a student who sounds inconsistent may in fact be using a mental model which is different from the scientific one, but which is nevertheless well-defined and internally consistent, is usually not explored in a systematic way. (p. 52)

Teaching students to actively search for discrepancies and inconsistencies among their ideas may be a productive endeavor, but caution must be exercised to ensure that what may appear discrepant to an onlooker not be automatically labeled as something that should be discrepant to the student. The willingness to seek consistency in one another's ideas emerges as an important theme in both Section 4.3.5 with respect to student-student interaction and in Section 4.4 in terms of student-teacher interaction.

### 2.4.2. Moving beyond resolving discrepancy.

Concern regarding the source(s) of motivation for resolving discrepancy is likely closely related to the source of motivation to seek new knowledge that extends beyond one's current ideas. Wong's (1996) discouragement with his students' lack of regard for a need to explain may likely be explained, at least in part, by the following statement from Carey et al. (1989):

> Inhelder and Piaget argue that before the ages of 13 to 15 years, children are not able to entertain or evaluate hypotheses because the logic of confirmation is not available to them, but it is equally likely that the problem is understanding the point of experimentation. (p. 516)

It appears that a large part of the problem is that the questions being investigated are not the students' own.

Where do children's own questions come from? Are some students simply more motivated than others to understand why things happen? Are the students who perceive and persistently tackle discrepancies also the ones who actively seek new information to add to their knowledge structures? What prompts them to do so? What role does the seeking of broader patterns and generalizations play in the formulation of new questions? By understanding the motivations that lie behind children's own questions, perhaps teachers would be better equipped to incorporate appropriate stimuli into their introductions of new concepts. Although definitive answers to these questions are not wholly evident in the data gathered for this study, the developmental framework developed in Section 4.3.1 supports the idea that students' understandings of the nature of scientific inquiry may play a consequential role in the types of questions that students choose to investigate and in the depth to which they do so.

### 2.4.3. Unarticulated / vague conceptions.

Several authors have expressed a concern with the implications of the idea that students do not always have well-formed conceptions to articulate in the manner that conceptual change models of constructivist teaching practices would suggest (Gunstone, 1994; Nersessian, 1992b; Strike & Posner, 1992; Vosniadou, 1994; White, 1994). It should be noted, however, that these ideas are not new. Piaget (1967) referred to conceptions generated by his subjects as a result of his discussions with them as "liberated convictions" (p. 11). There also seem to be parallels between the reification of vague ideas and pre-paradigmatic science. Strike and Posner (1992) suggested that "people may not have beliefs about how something works so much as they have images of how it works or 'body language' about how it works," and claim that "these representations may function as a source of initial and incorrect 'intuitions'" (p. 156). They also propose that "misconceptions may exist as various factors in a conceptual ecology that function to select for or prefer some representation of a misconception when the opportunity to do so exists" (pp. 156-157). This is similar to di Sessa's (1983) description of the role of "p-prims," which he defined as a "rich but heterarchical collection of recognizable phenomena in terms of which they [children] see the world and sometimes explain it" (p. 16).

"P-prims" themselves need not be misconceptions, but they may be applied or overgeneralized in ways that create misconceptions. di Sessa (1983, 1988) expressed the idea that helping students to integrate existing knowledge properly is more important than providing direct challenges to incorrect ideas that they may hold. According to Brown (1993), students' conceptions in physics are "constellations of these p-prims applied to particular situations" (p. 1276). He referred to such constellations of "p-prims" as "core intuitions," which he described as implicit and domain-general. According to him, these intuitions (when inaccurate) may be strong barriers to conceptual understanding. In this sense, he appears to support di Sessa's (1983, 1988) emphasis on the manner in which accurate understandings may be combined in ways that generate misconceptions. The idea that misconceptions are often based on logical understandings that are combined in non-scientific ways emphasizes the need to present students with events or ideas that contradict the "core intuitions" rather than the components that comprise them.

One of the content categories that White (1994) identified as having a possible effect on student learning deals with topics for which students are unlikely to have articulated theories (e.g. the structure of matter). He claimed that "discussion of views in advance might be counterproductive, encouraging students to form a view that may be contrary to the one the teacher plans them to have" (p. 257), and argued instead that a transmissive model may be more appropriate in such situations. In light of the prior discussion regarding "p-prims" (di Sessa, 1983, p. 16) and "core intuitions" (Brown, 1993, p. 1276), it seems likely that these factors will influence the development of new ideas regardless of whether they exist in an articulated format. In fact, the diversity of mental models of the atom that Harrison and Treagust (1996) elicited from a group of subjects who received common instruction on the structure of the atom may serve as a case in point. By having students articulate their own theories, it becomes possible to see how diverse elements derived from prior knowledge influence the development of their ideas. By understanding the roots of misconceptions that lie in learners' conceptual frameworks, perhaps the roots of conceptual understanding would be closer at hand. This would allow a more effective approach to dealing with the constraints identified by R. Kitchener (1992):

> . . . there are rational (morphological) constraints operating to constrain the very *form* of the trajectory of such a stage law, for example, any conceptual stage $S_j$ subsequent to $S_i$ must incorporate the epistemic competence of the preceding stage. The similarity to morphological constraints in biological evolution should be apparent. (p. 127)

Finally, regardless of the nature of misconceptions inherent in students' newly formed or well-entrenched theories, the process of idea formation is fundamental to generating knowledge and understanding in science. Conceptual change is only one aspect of this type of learning. Students need to learn to extend their knowledge by putting together ideas in systematic ways and then evaluating those ideas. The generation and evaluation of theories are discussed in the next two sections.

#### 2.4.4. Theory generation.

> *By what processes are new scientific representations constructed? The prevailing view among philosophers is that the discovery processes are too mysterious to be understood. This view receives support from numerous stories of discovery through flashes of insights of geniuses, such as Kekulean dreams and Archimedean eureka-experiences. What is omitted from such renderings are the periods of intense and often arduous thinking and, in some cases, experimental activity that precede such "instantaneous" discoveries.*
>
> (Nersessian, 1992a, p. 11)

If students have only vague conceptions of many scientific concepts, then the importance of emphasizing idea generation in science education is clearly critical. Difficulties associated with the lack of knowledge of how students generate ideas is compounded by the fact that even historical accounts of the development of science tend to emphasize the products rather than the processes of scientific development. T. Kuhn (1970) commented on the sparsity of the record of the difficulties that scientists throughout history have faced in developing their respective fields. If these difficulties tend to be glossed over, how much more must the internal struggles and confusions that took place in their minds be effectively lost. According to Duschl et al. (1992), the development of "more cognitively oriented accounts of the development of the many scientific theories that have not yet been investigated in this mode" (pp. 40-41) is an important area of research that will help inform the practices of science education. Nersessian (1992a, 1992b) also emphasized the need for greater attention to the processes by which scientists throughout history have generated and evaluated their ideas.

Some would argue that understanding the processes involved in idea generation and evaluation is unnecessary and perhaps impossible. With regards to theory generation by Nobel Prize winners, Marton, Fensham, and Chaiklin (1994) concluded that:

> All the participants commenting on the issue seem to agree that the fruits of scientific intuition are not derived or cannot be derived from what is consciously known. One reason seems to be that it is too difficult to find the necessary combination of the information available through conscious logical reasoning and another reason is that all the necessary information is simply not there. (p. 462)

It is possible, however, that for experts such as these, the processes by which they think are more elusive than they would be in a study of children. Such processes may have reached a level of automaticity that makes them irretrievable by conscious thought. In addition, the authors had only the recollections of the subjects to guide their interpretation. Collecting information on thought processes as the subjects attempted to develop their ideas may have provided different results. Work in the areas of analogy and imagistic reasoning, which are not entirely exclusive, seems to demonstrate particular promise in understanding the processes of scientific idea generation.

The pervasiveness of analogy has been well documented as a source of scientists' ideas (Bronowski, 1964; Glynn, 1991; Nersessian, 1992b). Duit (1991) commented that learning "fundamentally has to do with constructing similarities between the new and the already known. It is precisely this aspect that emphasizes the significance of analogies in a constructivistic learning approach" (p. 652). Throughout this discussion, the term "analogy" is used to refer to a perceived relation between two objects or situations that differ in one or more ways and between which explanatory structures may be transferred. The term "target analog" is used to refer to that portion of the analogy that the person creating it seeks to understand. "Base analog" indicates the usually more-familiar situation that is used to generate a better understanding of the target (Gentner, 1983).

According to Clement (1988), base and target analogs should be at the same level of abstraction, thereby helping to eliminate what he sees as confusion between examples and analogies. He used what he described as a non-analogous relationship between a bird and a robin to illustrate this idea (p. 569). However, in terms of the definition proposed here, the perception of a relationship between a bird and a robin and the subsequent transfer of explanatory structure from one to the other would qualify as an analogy. The recognition of a robin as an example of a bird can only come about through this analogical process. Gentner (1983) also attempted to distinguish analogies from "literal similarity" (what Clement calls examples) and from abstractions (p. 155). According to her, literal comparisons involve components that share many common attributes. She distinguished analogy from abstraction in her description of an abstraction as a situation in which the base analog is an abstract structure from which few attributes and many relations may be mapped. A true analogy, by comparison and contrast, also maps few attributes and many relations, but has a base analog with a concrete structure. She admitted that, by this definition, "the contrast between analogical and literal similarity is a continuum, not a dichotomy" (p. 161). The same may be said of her attempt to distinguish analogy and abstraction. The definition used here avoids the confusion that such arbitrary points of division may effect. Both literal similarity and abstraction are encompassed in a definition that describes analogy as a perceived relationship between two objects or situations between which explanatory structure may be transferred.

Clement (1988) excluded extreme cases from his definition of analogy, reasoning that "certain extreme cases, such as considering a very narrow or very wide spring, were not counted as analogies, because width is considered to be a problem variable, not a fixed feature" (p. 569). He also excluded parts of the original system; e.g. a "single, unmodified coil of the spring" (p. 569). The definition used here is inclusive of both extreme cases and parts of the original system, because explanatory structure from the extremes may be transferred to the non-extremes, and explanatory structure from parts may be transferred to wholes. This definition is consistent with his exclusion of cases that merely identify surface similarity and that are used only as descriptive aids.

Unfortunately, the primary role of analogy as evidenced in the research pertaining to science education appears to be that of a teaching tool whereby teachers provide analogies for their students (Dagher, 1995; Duit, 1991; Glynn, 1991, 1994; Mason, 1994). Depending on the particular approach taken, either the student or the teacher is then responsible for matching salient elements in the base and the target. Although such practice may have value when properly used in certain contexts, it does not allow students to participate fully in the scientific process. The development of analogies is an important part of scientific thinking. As Duit (1991) stated, "If it is accepted that science instruction should not only teach scientific knowledge but also scientific metaknowledge, then the role of analogies and metaphors in science must be considered an essential aspect of science instruction (p. 668).

Studies by Clement (1981, 1982, 1988, 1989a, 1989b), J. Osborne (1996), and Wong (1993a, 1993b) regarding the role of learner-generated analogies in idea-generation have gone far beyond the constraints that limit the studies based on teacher-generated analogies. The methods employed by these researchers also avoid some of the difficulties associated with the ex post facto research that is typical of the historical studies and retrospective interviews discussed earlier.

Clement (1981) described the analogizing process as occurring by means of the following four steps:

> 1. Given the initial conception A of an incompletely understood situation, *the analogous conception B is generated*, or "comes to mind";
>
> 2. *the analogy relation between A and B must be "confirmed";* [This idea is discussed in greater detail in Section 2.4.5.]
>
> 3. *conception B must be well understood*, or at least predictive; and
>
> 4. *the subject transfers conclusions or methods from B back to A*. (p. 137)

He emphasized that these steps may occur in any order and that subjects may move back and forth between steps. The first step is particularly important to the current discussion: How do ideas "come to mind"? Clement proposed three mechanisms by which analogies may be generated:

1. "generation from a principle" (p. 139): the analogy occurs as a result of perceived similarities between the abstractions of two or more different objects or situations; i.e. two objects or situations are perceived as belonging to a common and more general class of phenomena
2. generative transformation: some aspect of the original situation is modified to create a more familiar situation that can then be analyzed
3. associative leap: a perceived similarity between certain aspects of the target and base causes some aspect of the original problem to remind the subject of another object or situation.

As is discussed in Section 2.4.5, generative transformations are typically analogies for the purpose of evaluating other analogies, whereas the other two are used more directly in trying to explain unknown phenomena.

Although Clement's (1981, 1982, 1988, 1989a, 1989b) and Wong's (1993a, 1993b) ideas may hold important keys to understanding and promoting the process of idea generation in the science classroom, their work involved only adults, and only Clement dealt with the sources of their ideas. Recent work by Cosgrove (1995) provides some support for the idea that children (in this case, 14 year-old boys) are capable of generating analogies that may serve as the basis for further experimentation, but he did not analyze the sources of the analogies that his subjects used. Developing a greater understanding of how children generate ideas is a major focus of this study, and is addressed in Section 4.3.2. As Millar (1989) commented,

> From this point of view, a child, when offering a prediction or explanation in an interview about phenomena, for example, is not seen as deriving her or his answer by applying some basic 'laws' (or 'alternative laws') about the branch of science in question to this particular instance. Rather, she or he is seen as

> noting similarities or making analogies between the current problem situation and another recalled situation for which the answer is known. The basis for all prediction, and therefore of understanding, is a set of base-level, or 'paradigm' situations, which the child really "knows" about. From this perspective, understanding *why* children give the answers they do would become an important focus for research, as it would give insight into these fundamental paradigms. Having heard a child's prediction or explanation, we would want to enquire *why* they think this will happen or *why* they put forward this explanation. (p. 594)

### 2.4.5. Theory evaluation.

> *If I am correct, how should science education be changed? Science education must be viewed as cognitive change, and this means epistemic change. It will not do, therefore, merely to get students to change their beliefs or cognitive structures, for after all this could be done, as a Skinnerian would suggest, by changing the reinforcement contingencies. What is important is not mere belief-revision, but rather belief-revision based upon epistemic grounds, motivating the student to change his / her beliefs for good epistemic reasons. They must (on some level) come to see the epistemic inadequacy of their belief structures and, if I am correct, the motivation for such change must be epistemic in nature, not merely psychological.*
>
> (R. Kitchener, 1992, p. 132)

The manner in which students decide if a particular idea has merit, and if they should reconstruct their ideas, is of critical importance to science pedagogy. According to Carr et al. (1994),

> If science is not a set of truths which exists independently of people, then in the construction of this structured complex of ideas there will often need to be *changes* made to ideas. This process of changing prior ideas is also the core activity of education so the issue of acceptance or rejection of a new idea is an important one both for science and for science education. (p. 157)

They went on to provide criteria by which new ideas can be evaluated and included parsimony, elegance / coherence, and the ability to explain current evidence and predict new outcomes in their discussion. These ideas are consistent with Posner et al.'s (1982) claim that a new theory should be intelligible, plausible, and fruitful. But how are such judgements arrived at? How does one evaluate the parsimony, elegance, predictive capability, intelligibility, plausibility, or fruitfulness of an idea? Are all students concerned with these features of a theory? As was the case with idea generation, not everyone shares the optimism that understanding the mechanisms of theory justification is possible. Duschl et al. (1992) made the following comment regarding the mental processes involved in theory justification:

> One of the important lessons to be learned from both cognitive psychology and history of science is that the rules by which scientists apply theories to experimental situations and the rules by which they evaluate modifications of a theory are quite deeply implicit. . . . The process of articulating them is unnecessary even if it is possible. (p. 30)

Many different evaluative techniques have been identified in the literature. The pervasive role of analogy in generating scientific ideas makes evident the need for effective methods of evaluating these analogies, and, indeed, the literature a considerable amount of information pertaining to this topic is available. Wong's (1993a, 1993b) studies emphasized the role of analogy in question-generation, whereas Clement (1981, 1986, 1988, 1989b) discussed the role of generative transformations in the form of bridging analogies in evaluating the validity of analogies. Clement (1988) and Nersessian (1992a, 1992b) focused on the role of thought experiment in evaluating ideas. Clement (1994) and Nersessian (1992b) discussed the related but distinct role that imagistic reasoning plays in theory evaluation. Finally, the search for general, widely applicable principles seems to play an important role throughout the meaning-construction process. Contrary to Duschl et. al's (1992) claim, Nersessian's (1992a, 1992b) historical analyses of the manner in which scientists construct meaning have made evident interesting patterns regarding the manner in which they evaluate their ideas. In addition, as in the case with his studies of theory generation, Clement's (1981, 1986, 1988, 1989b) accounts of theory evaluation have moved beyond historical and ex post facto accounts and provide valuable data that make these processes more explicit than some would previously have deemed possible. Clement's (1981, 1986) work with experts, Nersessian's (1992a, 1992b) historical work, J. Osborne's (1996) work with high school students, and Wong's (1993a, 1993b) work with science teachers all point to the emergence of some strong themes in terms of theory evaluation.

Throughout the following section, emphasis is placed on the mental evaluation of theories. This is not meant to undermine the importance of empiricism. Clearly, empirical data provides essential evidence with which to evaluate theories. In addition, some evaluative techniques, such as recognizing confounding variables, understanding the need for a control, providing definitions of constructs, developing accurate systems of measurement, and using sufficient data are important factors to consider in both contexts. The mental evaluation of theories plays a vital role in the development of the understandings and of the questions that necessitate actual physical experimentation. Unfortunately, it seems that in the field of science education, an undue emphasis has been placed on the physical aspects of scientific activity at the expense of the often more implicit mental processes that are so fundamental to its very nature.

#### 2.4.5.1. Techniques for evaluating learner-generated analogies.

Clement (1981, 1986, 1988, 1989b), and Wong (1993a, 1993b) clearly demonstrated the richness of the information that can be provided by interviewing problem solvers as they vocalize their attempts to explain specific phenomena. In addition to emphasizing the importance of the thinking processes of science, analyses of these interviews have provided important insights into why many of the analogy-based pedagogical techniques that rely on teacher-generated analogies have so often failed.

Wong (1993a, 1993b) displayed rich insights regarding the importance of the question-generating capacity of analogies in his studies regarding the use of learner-generated analogies to develop explanations for various air pressure phenomena. He described how analogies often prompted his subjects to revise, elaborate, or replace their theories and emphasized the manner in which successive analogies with increasing explanatory power were particularly useful. The chains of analogies observed in Clement's (1982, 1988) expert problem solvers served much the same function, although he did not explicitly acknowledge the question-generating capacity inherent in these analog chains. Based on the portions of transcribed interviews that Wong (1993a, 1993b) provided, it appears that the questions stimulated by the analogies were based primarily on gaps in knowledge that were made evident as the learners questioned the appropriateness of mapping particular elements of the source to the target analogs. Hardwicke (1995) referred to the "grey area consisting of aspects of the source that are not definitely positive or negative" as the neutral analogy. In Wong's (1993a, 1993b) studies, the development of successive analogies with fewer and fewer neutral components was effectively used by learners to evaluate and modify their own ideas. The ability to generate a series of analogies in this fashion was observed in several of the students in the current study. These observations are described and analyzed in Section 4.3.2.

Clement (1981) identified extreme-case reasoning and bridging as two important techniques for theory-evaluation. Nersessian's (1992a, 1992b) explanation of "limiting case analysis" (p. 56) is very similar to Clement's discussion of extreme-case reasoning, and she documented its use by Galileo in determining the effects of different media on the speed of fall of different objects.

Both Clement (1986) and Nersessian (1992b) described a thought experiment performed by Galileo in which he imagined dropping a heavy object tied to a light object. In so doing, he was able to point out the contradictory implications of the heavy-objects-fall-faster hypothesis that he was attempting to refute: The combined body should fall more quickly due to its increased combined mass as well as more slowly due to the retarding action of the smaller object. Clement (1981) included this as an example of a bridging analogy, which he defined as a case in which "subjects are observed to generate an *intermediate case* when they refer to a situation that has aspects in common with two previous situations A and B" (p. 138). In addition to documenting historical instances involving the use of bridging analogies (1986), his interviews with experts provide detailed evidence of their use (1981, 1986, 1988, 1989b). For example, to determine why different spring widths respond differently to the attachment of an equal weight, one of his subjects compared the spring to the more familiar phenomenon of leverage in a bending rod (1989b). The subject then used extreme-case reasoning to consider the effect of extremely wide or narrow springs on the amount of stretching that would occur with the same weight attached. However, he was troubled by the constant slope in a bending spring. A bending lever gets progressively steeper, and he was therefore unsure whether the bending rod could be seen as analogous to the spring. This prompted him to generate the intermediate case of a zigzag to mentally test his idea. Still unconvinced, he tried to figure out how the circular nature of the spring might make the two situations different, and thereby invented a square coil that retained qualities of the lever at the same time that it incorporated the circularity that he felt was lacking in the zigzag. The square coil constitutes a bridge in that it provides an analogical situation that retains the quality of the zigzag spring in a context that includes circularity. Extreme-case reasoning again became evident as the subject considered the effect of triangle, hexagonal, and other polygonal coils approximating a circle on his new model.

Both bridging and extreme-case reasoning appear to be used to determine whether an identified variable is in fact salient to the phenomenon being investigated. In the form of a bridge, this involves the evaluation of the validity of an analogy through the invention of a new analog that alters the negative component of a previous analogy. In the form of an extreme case, explanatory structures from the extremes are used to evaluate the salience of a problem variable in its non-extreme form.

It is encouraging that historical studies and studies of experts as they work have generated such similar data. As was the case with theory generation, however, the work done to date has dealt primarily with adults. According to Nersessian (1992b), "A major problem for historicist philosophers has been *how to go from a case study to a more general conclusion* [italics in original]" (p. 35).

Cosgrove's (1995) provided important evidence that students use many of the same processes as experts as he explained how they generated and evaluated an analogy for electricity. His students began with a single analogy generated by one member of the class, but elaborated and refined it throughout the unit of study in a manner that resembles that used by Wong's (1993a, 1993b) subjects. Based on the interview transcripts that Cosgrove (1995) provided, it appears that the students' methods of evaluating the analogy were largely based on thought experiments that could be classified under Clement's (1981) generative transformation category. The students often followed up their thought experiments empirically, thereby confirming or rejecting the predictive implications of the analogy and providing evidence of the need for its modification or rejection. In addition, sometimes the teacher suggested situations and asked the students to explain them in terms of their analogy. This also provoked modification and elaboration of the analogy at several points in the unit. Further examples of students engaging in this type of work are necessary to understand more fully the degree to which they are capable of generating and evaluating their own analogies, the sources of the analogies that they use, and the manner in which they evaluate their analogies. Each of these points is addressed in Section 4.3.2. The teacher's role in presenting discrepant or thought-provoking situations and questions at critical points in the discussions and activities is also a matter of considerable import and is discussed in Section 4.4.4.

#### 2.4.5.2. The role of imagery.

Often, mental models are used to provide concrete analogies by means of which complex and / or invisible phenomena can be more easily imagined and therefore manipulated mentally. It is common for a mental model to act as a base analog (Duit, 1991). Nersessian (1992b) claimed that such models form "an intermediate level of abstraction between phenomena and mathematical forms of representation" (p. 25). Brown and Clement (1989) explained the importance of explanatory models to successful bridging analogies in the following manner:

> Such explanatory models might seem more plausible or compelling to the student than an expedient analogy [which shares only its abstract form with the target], since key elements of the model are seen as actually

> operating in the target. Thus the model involves concrete as well as abstract similarity in that the model provides a structure or mechanism that could plausibly be imagined in the target. (p. 255)

It is interesting that, in this description, the abstract explanatory models appear to help the problem solvers recognize causal mechanisms common to the base and target analogs in a more concrete manner. The use of this strategy is very evident in the dialogue provided in Section 4.3.2.

### 2.4.5.3. The search for broader principles.

It appears that during the process of constructing meaning, the search for unifying principles plays a critical role in the ongoing search for connections between ideas. It can prompt the search for and evaluation of analogy, prompt the generation of new questions, and can serve as an evaluative measure in relation to what Posner et al. (1982) described as "skepticism for excessive ad-hocness" (p. 226). Sometimes broader principles are represented as imagistic models, and they may represented mathematically. Although the search for widely applicable principles permeates the history of science, there appears to be little in the literature in terms of specific analysis of the manner in which students seek unifying frameworks for their ideas. This topic is addressed in Section 4.3.3.

### 2.4.5.4. Why teacher-generated analogies don't always work.

> *One of the great experiences of my scientific career was to discover in high school that I could profitably think about a problem for weeks, that I could get valid insights, make progress, see things gradually fall in to place, rather than just "find the solution" like a needle in a haystack. Yet I had this experience in none of my classes, but on an exam for a summer science program for which I was applying. Indeed the vast majority of work done by students in school classes is of the 20-minutes-or-less-per problem type. This is hardly fertile ground to promote awareness of learning processes that may be months or years long.*
>
> (di Sessa, 1988, p. 69)

Given that talk of students working in the manner that scientists do is often used as a rationale for the use of analogy in the science classroom (Glynn, 1991; Pressley & Woloshyn, 1995), it is interesting that so few of the studies that have been conducted to date have investigated learner-generated analogies. The studies by Clement (1988), Cosgrove (1995), and Wong (1993a, 1993b) discussed in the previous section are notable exceptions, but Cosgrove's is the only one that involves children. Another difficulty with most of the studies pertaining to analogy use in the science classroom is that they commonly deal with convergent problem-solving situations. Only a small number of the studies done to date have demonstrated the value of analogies in generating questions that are sparked by the need to evaluate the strengths and weaknesses of a particular analogical relationship (Clement, 1989b, Cosgrove, 1995; Hardwicke, 1995; Lawson, 1993; Sutton, 1993; Wong, 1993a, 1993b). In short, the research regarding how children use analogies to make sense of scientific concepts is based almost exclusively on teacher-generated analogies, and almost invariably on attempts to steer students toward pre-determined conclusions. In the section that follows, some of the limitations of teacher-generated analogies are explored. To examine the role of analogy in terms of the scientific thinking that takes place in the science classroom, it is necessary to examine how students formulate and modify analogies to construct meaning of the phenomena they are investigating. Understanding how they do so is an important component of this study and is addressed in Section 4.3.2. Certainly, scientists create their own analogies to help them make sense of new phenomena in light of their own prior knowledge.

When the subjects in Clement's (1988), Cosgrove's (1995), and Wong's (1993a, 1993b) studies selected their own analogies, they were able to make meaningful connections between the base and target analogs with which they were working. This encouraged independent problem solving. On the other hand, many studies involving teacher-generated analogies have emphasized the problems associated with overgeneralization (Gentner, 1981; Glynn, 1991; Harrison & Treagust, 1996; Mason, 1994; Pressley & Woloshyn, 1995). This appears to be due to two factors: (a) each student's background knowledge regarding the base analog is different than the teacher's and / or textbook author's and (b) many of the studies involving teacher-generated analogies place an undue emphasis on the answers rather than the questions that such analogies can stimulate.

The ability to judge whether chosen connections between base and target analogs are valid or helpful requires a certain degree of background knowledge of both components of the analogy. It seems that many researchers who have attempted to bring about conceptual growth or change by means of analogy have been unsuccessful, because the students involved failed to accept the situations as analogous and / or did not map them in a manner consistent with the teacher's intentions. In many cases, this appears to be due to insufficient understanding of the source and / or target analogs (Clement, 1993;

Harrison & Treagust, 1996; Mason, 1994; Vosniadou, 1989). Dagher's (1995) summary of fifteen studies of analogy-based science instruction contains many examples of these concerns.

Mason's (1994) study clearly demonstrates the problems that may occur when there is insufficient understanding of base and target analogs. In her attempt to have her students develop an analogical relationship between a postal delivery system and the human heart-lung system, she assumed that the mail-delivery system was familiar to all of her students, directly taught the heart-lung system, and had the students look for similarities between the two systems. However, some of the children did not have a clear understanding of the mail system (the base analog). For example, several were unaware that the postman had to go back to the post office after picking up the mail from the mailboxes. This led them to believe that blood goes straight to the lungs after returning through the venous system of the body. In itself, the students' lack of understanding of the postman's journey need not have posed a problem. Had the children been encouraged to create questions regarding the elements about which they were uncertain (e.g. Does the postman go straight back to the post office?), they may not have jumped to erroneous conclusions. In addition, they may have developed a better understanding of both the postal system and the functioning of the heart and lungs. Mason, however, went so far as to state that "teachers who encourage learners to generate their own analogies should check possible inappropriate selection processes, inferential errors, misperceptions of their usability [sic]" (p. 183). Harrison and Treagust (1996) expressed a similar sentiment in their assertion that, because students need guidance in understanding the valid and invalid features of a particular analogy (in this instance, different models of the atom), "the unshared attributes should be identified for the students by the teacher" (p. 521). Mason's (1994) conclusions regarding overgeneralization are also similar to those expressed by Glynn (1991) in his "Teaching With Analogies" model, although he later made explicit reference to the need for future research to focus on "determining how students can construct effective analogies for themselves, independently of teacher and textbook authors" (1994, p. 22). The students in this study provided ample evidence of their ability to generate and evaluate their own analogies, and the manner in which they did so suggests the existence of a developmental progression in students' understanding of analogy (see Section 4.3.2). It appears that by helping children to more effectively recognize and capitalize on the benefits of analogy while avoiding the trappings of overgeneralization, they could learn to use analogy very effectively.

If students are expected to generate questions rather than answers, what could otherwise become overgeneralizations could become important questions to guide the uncovering of new layers of understanding. In this way, the children's analogical reasoning and their ability to generate meaningful questions could both be strengthened. Furthermore, their approach to learning would be one that is based on rational thought rather than blind acceptance of principles presented by an external authority.

Mason (1994) claimed that the children "mapped irrelevant features, but hardly ever inappropriately, in drawing inferences on the new domain" (p. 181). Understanding which components are relevant and irrelevant is a function of the level of understanding the students have of the base and target analogs. If students were involved in selecting an analogy to help them develop their own understanding, selection of relevant features could have been a much more rational process that may have helped the students to avoid problems associated with lack of belief in the presented analogy and with poor knowledge of the base analog.

The ability of even very young children to generate analogies has been documented (Gardner, 1982; Vosniadou, 1989). As Vosniadou claims,

> ...analogical reasoning is available to children. Like adults, children can identify the similarity in the structure between two analogs when this structure is part of their representation of the source and target systems. Moreover, it appears that children can use similarity in salient properties between two systems for discovering structural similarities between them, just like adults do. It is concluded that what is developed is *not* the analogical mechanism itself but the conceptual system upon which this mechanism operates. (p. 414)

It is interesting that the observed tendency of children to overgeneralize effectively demonstrates their ability to map corresponding parts of potential analogs.

Mason (1994) claimed that her emphasis on promoting reflective awareness of the importance of analogy in the conceptual change process was fostered by promoting metacognitive awareness and was effective in fostering conceptual growth as well as in promoting an awareness of the role of analogical reasoning in the conceptual change process. However, her conclusions appear to be based on two fundamental flaws in her reasoning.

To begin with, although Mason's criteria for scoring a three (the highest possible score) for "awareness of the use of the analogy in changing initial mental models" (p. 177) included explicit mention of the usefulness of the postal analogy to alter initial conceptions, only two of the six examples of student responses that she cited even mentioned the postal system (see Examples 4 and 6 in Appendix A). The other four provided clear evidence of the students' awareness of changes to their ideas, but no evidence whatsoever that the postal analogy played a role in effecting these changes. As a result, the students' awareness of changes to their ideas was measured in place of their awareness of their use of analogical reasoning to do so. Mason's claim that "A high correlation was also found between conceptual understanding of the new topic and metaconceptual awareness of the meaning and purpose of the analogy in learning new science contents" (p. 180) is therefore not clearly supported.

Mason assumed that the changes in her students' ideas were due to the use of the postal analogy rather than to the content taught directly prior to introducing the analogy. Evidence that students are able to explain clearly the relationship between the mail delivery and the heart-lung system in no way emphasizes the importance of analogy in promoting such understanding. Due to the manner in which the analogy was presented, clear knowledge of both systems was a prerequisite for the ability to describe the relationships between them. Describing the analogical relationship between the postal system and the circulatory system could well have occurred ex post facto. It may have served as a memory aid, but used in the manner that it was, was not necessarily an effective part of the meaning-generation process.

Mason's study should help to clarify why studies dealing with teacher-generated analogies as frameworks from which students are expected to gain deeper understandings of particular scientific concepts don't always work.

#### 2.4.5.5. Using analogies as a teaching tool to foster conceptual change.

Different strategies have been suggested for minimizing some of the problems discussed in the previous section. Some of these, such as comparing the merits and drawbacks of multiple analogies (Glynn, 1991, 1994; Harrison & Treagust, 1996; Spiro, Feltovich, Coulson, & Anderson, 1989) and directly presenting the strengths and limitations of a given analogy (Glynn, 1991), have continued to ignore the scientific thinking processes that make analogy so valuable. Although these strategies may help students to gain a better grasp of content, it is questionable that they will help them develop the ability to use analogical reasoning to generate their own questions and hypotheses unless they are used in the context of argument as ideas are developed. Taken out of context, the use of analogy is likely no more productive than the isolated practice of process skills.

The use of bridging analogies as a teaching tool also involves teacher-generated analogies (Brown, 1992, 1993; Brown & Clement, 1989; Clement, 1993; Clement, Brown, & Zietsman, 1989). However, the description of the manner in which they are used in various studies clearly places them within a pedagogical environment that actively promotes scientific thought:

> Although these interviews could be called tutoring interviews, the students were informed that the interviewer would take a "devil's advocate" stance to foster discussion. In this way students were encouraged to adopt only those ideas that seemed reasonable to them, as they would be unsure whether the arguments the interviewer was advancing were "correct" or simply made to encourage discussion. (Brown & Clement, 1989, p. 241)

As Duit (1991) commented, such a strategy is " very student-oriented, involves main aspects of negotiation of views, and employs aspects of Socratic dialogue" (p. 665).

The use of bridging analogies in cases where conceptual change is needed to make students' ideas consistent with scientific ideas supports White's (1994) suggestion that different teaching strategies may be more appropriate in cases where the presence of alternative models with convincing explanatory power could otherwise confound the learning process. It is also consistent with Duschl et al.'s (1992) speculation that student conceptions requiring radical restructuring may need to be approached from a context of justification approach. To reiterate, however, such an approach need in no way undermine the overall framework of a context of development. The inclusion of argument is a critical part of the context of development. Perhaps teachers should develop a large repertoire of effective bridges (and other types of arguments), particularly regarding concepts where persistent misconceptions are known to occur. This idea is discussed further in Section 4.4.4.

#### 2.4.5.6. So when should theories be modified?

The criteria discussed to this point have described the manner in which scientists and students evaluate, expand, and modify their theories, but have not offered guidance regarding when these changes should occur. Perhaps this is a moot point in that one cannot simply change his or her ideas because the evidence seems to point in a certain direction. To shift theories, one must be able to make sense of the world with the new ideas. This may not be something that one can simply decide to do. T. Kuhn (1970) made a similar point in his discussion of paradigm shifts in the scientific community:

> That transition is not, however, one that an individual may make or refrain from making by deliberation and choice, however good his reasons for wishing to do so. Instead, at some point in the process of learning to translate, he finds that the transition has occurred, that he has slipped into the new language without a decision having been made. (p. 204)

Perhaps having students reflect on their own decisions to accept or reject certain ideas and helping them generate an ongoing list of reasons for why they do so would provide them with a more abstract and general representation of their reasoning that could be more easily transferred to other relevant situations. Carr et al.'s (1994) emphasis on the importance of having students debate their reasons for changing their ideas makes sense in terms of helping them to better understand both the process of scientific knowledge construction and their own thought processes. As students reflect on their ideas and develop names and associated conceptions for both productive and faulty arguments, they may become more skilled at evaluating their ideas. Reflection on the processes of one's thinking is a type of metacognition and is discussed further in Section 2.5.

K. Kitchener and King (1981) focused more on broad views that students have of the nature of knowledge than they did on specific arguments regarding the epistemic status of a particular piece of knowledge. They identified seven stages of epistemological development through which they claimed that students pass. These stages are defined by varying degrees of reliance on external authority and differing views regarding the existence of objective reality. They exemplify a third type of metacognition that involves the nature of one's beliefs about learning and about scientific knowledge. Such beliefs may initially be primarily implicit in nature, but through participation in scientific activity and reflection on the development of ideas in this context, students may come to a more advanced understanding of the nature of scientific knowledge. In terms of classroom practice, R. Kitchener (1992) emphasized the importance of helping students come to see that:

> ...skepticism is an untenable epistemic position and correlatively that epistemological relativism is inadequate as a basis of knowledge. They must come to see that a standard of correctness of norm suitable for knowledge must be something in between skepticism and absolutism certainty, a fallibilistic criterion of adequate evidence. (p. 134)

Constructivist models of teaching appear to hold great promise in terms of providing a framework in which students learn to think scientifically. If concerns relating to an inordinate emphasis on conceptual change (at the expense of conceptual growth), and the absence of methods whereby the generation and evaluation of theories may be promoted, can be fruitfully addressed, a much broader view of science education may be put forth within this framework. Within it, what Watts (1994) referred to as "self-determination" must play a critical role: "...the person at the centre of the enquiry is not just an 'active meaning maker' but knows s(he) is too. That is, constructivism sees human actions, including learning, to be purposive, consciously aimed towards some end" (p.52). It is here that the importance of metacognition assumes importance.

## 2.5. The Role of Metacognition

Prior to embarking on a study that is dependent upon access to students' descriptions of their own thought processes, it was important to consider whether the students would be able to provide this kind of information. According to the monograph *Students' Thinking: Developmental Framework Cognitive Domain* (Alberta Education, 1987), students "become able to think about how they think" (p. 10) upon reaching the level of formal operational thought. It is apparent from other studies, however, that such reflection is not beyond students as young as eight and nine (Barell, 1995; Gunstone, 1994). The students who participated in this study provided ample evidence of their ability to reflect on their thought processes. Evidence of this is clearly documented in Section 4.2 and throughout the discussion of the development of the levels within each of three main developmental frameworks pertaining to theory generation and evaluation (Sections 4.3.1, 4.3.2, and 4.3.3).

Because the term "metacognition" is commonly used to represent quite different types of thinking, it is important to clarify what is meant by its use in the context of this study. Interpreted literally, metacognition means "thinking about thinking." In its broadest sense, this definition is accurate in terms of the current discussion. However, three distinct types of metacognition have already been introduced in various contexts within the discussion of constructivist teaching and learning: (a) thinking about ideas, (b) thinking about thought processes, and (c) beliefs about the nature of science and science learning. When students are metacognitively aware, they should gain an understanding of their own scientific knowledge and thought processes and the relation of these to the development of scientific understanding. This may allow them to monitor more consciously and to control the manner in which they learn. All three components of metacognition are critical and are usually considered complementary.

Gunstone (1994) incorporated each of these elements into his description of metacognition, noting that it "is a rather multifaceted one" (p. 133). He suggested that

> ...learners are appropriately metacognitive if they consciously undertake an informed and self-directed approach to recognizing, evaluating and deciding whether to reconstruct their existing ideas and beliefs. By informed, I mean recognize and evaluate, with an understanding of learning goals, of relevant uses of the knowledge / skills / strategies / structures to be learned, of the purposes of particular cognitive strategies appropriate to achieving these goals, of the processes of learning itself. Hence I argue that metacognition and conceptual change are totally intertwined. (pp. 133-34)

In his elaboration of this broad framework, he identified specific components that referred to thinking about ideas: "Integrating and extending refer to the extent to which the learner links what is being learned with previous school learning, with existing personal ideas and beliefs, with applications / examples / etc. in the 'outside world,' and with previous learning activities" (p. 135). Thinking about thought processes is also evident in his work. If students are able to "recognize and evaluate, with an understanding of learning goals, of relevant uses of the knowledge / skills / strategies / structures to be learned, of the purposes of particular cognitive strategies appropriate to achieving these goals" (p. 133), then they should be able to control their thought processes. Gunstone does not explicitly address beliefs about the nature of science and science learning, but his broader definition is inclusive of this idea: "Metacognitive knowledge includes knowledge of the nature and processes of learning..." (p. 134). To a large extent, this type of metacognitive awareness likely emerges as a result of the reflection that occurs as students think about the thought processes in which they engage while developing their own scientific understandings (Carey et al., 1989). It may also include learning about the historical development of scientific ideas and relating these ideas to their own learning.

As discussed in a previous section, having students identify or construct theories to help them recognize discrepancy between their own and scientific ideas is a fundamental tenet of constructivist learning (Hodson, 1996; Watts, 1994; Wittrock, 1994). In describing techniques to elicit students' ideas about scientific concepts, Kass (1992) explained that

> various metacognitive strategies (metacognition is thinking about one's thinking) such as concept mapping can also be used at this stage to reveal to both the students and the teacher the specific ideas they have. Self-awareness of what one does and does not know is an important part of reflective thinking and a guide to the next stage of knowledge building for both the teacher and the student. (p. S.3B-8)

Although Kass explicitly stated that "metacognition is thinking about one's thinking," in the context of the definition suggested here, her examples clearly place her meaning in the context of thinking about thought. Thinking about thinking would occur if the students recognized the importance of reifying their knowledge. At that point, they could do so consciously as part of an explicit strategy for making sense out of ideas and phenomena.

For purposes of this study, it is the students' reifications of their thinking that are most relevant. Their thoughts, however, provided the arena in which this was done, and therefore required careful documentation. In addition to serving as a window to understanding students' thought processes, the studies discussed in this section have indicated that metacognition plays an important role in the development of students' thinking skills in science. It was important to remain cognizant of these effects throughout the analysis of students' developing thinking processes over the course of this study.

## 2.6. Summary

In an attempt to relate school science to the actual practices of science, various approaches to science education have been reviewed. A constructivist model of teaching appears to have the most promise in achieving this goal. It is within this framework that content and process may be productively combined in a manner that exemplifies scientific inquiry. To construct meaning in science, students must use the processes of science. In so doing, they gain a firsthand appreciation of these processes. Although constructivist literature regarding the pervasiveness of persistent misconceptions in science is of great importance, more emphasis needs to be placed on the manner in which students generate and evaluate ideas in terms of both conceptual change and conceptual growth. For such an approach to be successful, teachers will need to gain a greater understanding of the manner in which children generate and evaluate their ideas so that they will be better able to facilitate these processes. Work by Gunstone and Northfield (1994) appears very promising in terms of helping teachers to understand their own thinking and the nature of science in a manner that is more consistent with authentic scientific thought. The implications for science teacher education discussed in Section 5.2 provide some preliminary suggestions regarding this matter.

# III. DESIGN FOR THE STUDY

*If our profession couldn't comprehend internal brain processes, it could focus on knowable external objects or events in the environment (stimulus) and the behavior (response) that emerged out of the unknowable cognitive processes. Thus, we became a profession of behaviorists, whether we liked it or not. We learned how to manipulate the student's environment to achieve the behavior we desired.*

(Sylwester, 1995, p. 3)

## 3.1. Introduction

To investigate the nature and development of children's thought, many variables need to be taken into account: "Everything has the potential of being a clue that might unlock a more comprehensive understanding of what is being studied" (Bogdan & Biklen, 1992, p. 31). Protocol analysis of classroom discussion and individual think-aloud interviews provided detailed information regarding the development of student's ideas as well as considerable information regarding the students' awareness of their own thought processes in doing so. Field notes collected during times when students were actively experimenting provided valuable information regarding the types of activity that different students chose to undertake. The combination of these approaches allowed a meaningful analysis of the complexity of the interactions among the many variables that appear to influence the manner in which children construct scientific understandings.

The ideas developed in Chapter Two served as an initial framework that guided the observation and analysis of the students' ideas and their methods for evaluating them. These categories were often modified to reflect actual student behavior, and some new categories were added. Much of the information pertaining to expert thinking was retained as an upper-level category in the developmental, levels-based framework constructed for each of the major themes that emerged. Gaps in the resulting framework prompted a return to the literature for further information regarding the development of the thinking processes in very young children. These are provided as a possible basis for the strategies used by the students in this study. In some cases, further research was also necessary to refine the description of expert processes to determine whether students' thinking processes could in fact be viewed as part of a progression toward these characteristics.

Class discussions were very motivating to the majority of the students and often brought out a wide variety of ideas for discussion. As a result, the transcriptions of these discussions were an incredibly rich source of student ideas and arguments. They also provided valuable information regarding the nature of the interaction that took place in the classroom during the observational period. The main drawback to this observational context was that the trajectory of an individual child's thoughts was sometimes lost as other students steered the discussion according to the manner in which their own thoughts interacted with what was being said. Conducting individual interviews with five students allowed a more sustained observation of the thought processes engaged by these children. Field notes regarding the types of activity selected by individuals were useful for identifying uninterrupted sequences of student-selected investigation, but were less detailed than the interviews and typically provided a brief description of the activities in which each student was engaged and their rationale for engaging in it.

Often, the perspectives sought from the students remained hidden in the world of their tacit understandings and had to be inferred from their comments and behaviors. Reflecting on thought processes while attempting to think through a problem proved very difficult for the students and often interfered with their thinking processes. However, their willingness to share tentative ideas and to talk aloud while they were thinking provided quite detailed information that made this type of analysis fruitful. The students were able to reflect on productive and non-productive contributions to class discussion and on factors that helped to facilitate their own methods of generating meaning. As they developed categories to describe these features, they began to use them in the context of general discussion and sometimes made conscious decisions regarding the effectiveness of certain techniques. This clearly affected the manner in which the students constructed and evaluated ideas. Identifying instances in which students explicitly mention specific strategies for generating and evaluating ideas is therefore an important feature in the analysis that follows. In so doing, it is important to distinguish between the identification of strategies during or after their use and the conscious selection of a particular strategy for which a student indicates intent to use prior to actually doing so. For example, one of the subjects in Clement's (1989b) study made the following comment:

> I feel as though I'm reasoning in circles. I think I'll make a deliberate effort to break out of the circle somehow. What else could I use that stretches...like rubber bands...what else stretches...molecules, polyesters, car springs [leaf springs]...what about a...two-dimensional spiral [watch] spring? (p. 353)

Clearly, this is a conscious attempt to make use of analogical reasoning (regardless of whether the subject calls it that) to generate new alternatives to the one that is frustrating him.

According to Merriam (1988), the ideal researcher plays a neutral role in terms of affecting the behavior of the participants in the study. However, in this case, a conscious and deliberate attempt was made to influence the students. This necessitated careful consideration of the interactions in which the students and I engaged so that the ways in which such influences were manifested could be made explicit. Merriam went on to qualify her initial statement in a manner that makes it consistent with this need. This is evident in her presentation of the following from Patton: "In reality, though, the question is not *whether* the process of observing affects what is observed but rather 'how to monitor those effects and take them into consideration when interpreting data'" (p. 95).

In attempting to help students develop a conscious awareness of their learning, this study shares elements of a group of studies through which the intent is to "encourage informants to gain control over their experiences in their analyses of them" (Bogdan & Biklen, 1992, p. 49). Therefore, the purpose of employing reflective strategies for gathering data was twofold: Students' reflections on their learning served as an important window for understanding how they used various strategies in their learning and also helped them to develop their own skill in this area.

It is only through the window of one's own beliefs and understandings that one can truly understand those of others. As a result, seeking differences between self and others is a critical part of this process. Throughout this study, I monitored and evaluated my own thought processes to develop a better understanding of scientific thought and to prevent biases based on stereotypical views of thinking that are rooted in my own. The manner in which this was done is discussed more fully in the discussion of the research diary. Truly, the observer is the instrument:

> . . . I believe that research focused on discovery, insight, and understanding from the perspectives of those being studied offers the greatest promise of making significant contributions to the knowledge base and practice of education. Furthermore, most case studies in education are qualitative and hypothesis-generating, rather than quantitative and hypothesis-testing, studies. Naturalistic inquiry, which focuses on meaning in context, requires a data collection instrument sensitive to underlying meaning when gathering and interpreting data. Humans are best-suited for this task – and best when using methods that make use of human sensibilities such as interviewing, observing, and analyzing. (Merriam, 1988, p. 3)

Through the use of interpretive interview and participant-observation techniques within a narrative-interpretive framework, access was gained to the sources of ideas and thought processes that the students used as they constructed understandings of a wide variety of natural phenomena. Specific uses of these techniques are outlined in the following section.

## 3.2. Specific Techniques

### 3.2.1. The subjects.

The classroom analysis portion of this study included the twelve members my Grade Five / Six class. The students all knew each other very well and had been together either every year or every other year (because of split classes) throughout their time in elementary school. In many cases, they were also involved in the same out-of-school activities. The school itself is an important part of the rural community in which it is situated, and it often serves as a gathering place for community events such as adult sports nights, 4-H meetings, and adult education programs.

The initial selection of the students was based upon varying ability to generate and evaluate ideas. Because these are the very factors that the study was designed to elucidate, detailed criteria for this selection were unavailable. Decisions regarding selection were largely based upon the frequency of ideas and the number and quality of the arguments generated by these students during regular classroom interaction. Clement (1989b) identified several explicit factors that he presented as critical to the success of one of his subjects in generating and evaluating an explanation for a particular problem, and these criteria were also taken into consideration in the selection of students for the current study:

1. "the subject's desire to ask 'why' questions and to seek a deep level of understanding beyond what is required for the solution of the immediate problem" (p. 375)

2. persistence in seeking scientific explanations "in the face of recognized internal inconsistencies and repeated failures" (p. 375)
3. "playful and uninhibited inventiveness in producing conjectures and modifications of the problem" (p. 375)
4. "a willingness...to criticize vigorously and attack the validity of his own conjectures" and an ability to "engage in a dialectic conversation with himself, proposing new ideas on the one hand and criticizing them on the other" (p. 375)

Three students with varying abilities were selected for a more in-depth and uninterrupted analysis of scientific thought processes. This group consisted of one female and two male Grade Six students. Samantha typically excels in academic areas, particularly Language Arts and Social Studies. She is also an extremely outgoing, energetic, and confident girl who easily assumes leadership roles in most situations. Keith is very inquisitive and has a tendency to work for very extended periods of time on a single problem. Although this often leads to difficulty in completing assignments in other areas, his attention to detail and to ensuring consistency among the components of the problems in which he engages are quite remarkable. Frank experiences considerable difficulty with academic classes, but excels in activities where he is given the opportunity to design, build, and troubleshoot his own creations. He is very concerned about appearing stupid in front of his classmates and withdraws quickly from class discussions when he is unsure about how to address a challenge posed by another member of the class. Frank is a talented athlete who spends a great deal of his out-of-school time attending hockey practice and games. So as not to hurt the feelings of other class members, other students who indicated a desire to participate were also included, and two additional male students in Grade Six were included in the individual interviews that took place at various points throughout the unit. As it turned out, the inclusion of five students allowed some very rich comparisons that may not have been as evident among the initial group of three students. Like Keith, Carl is an extremely inquisitive child who enjoys developing theoretical explanations for natural phenomena. He is an avid reader and has extensive background knowledge in many different areas. Although he is very capable of understanding the topics covered during his classes, his difficulty in completing assignments and projects is well known among his teachers. In contrast to Keith's situation, however, this tendency has more to do with his the manner in which he often diverts attention to other tasks that hold more interest at a particular moment. Like Samantha, Robert excels academically, but his extremely competitive nature heavily influences his approach to argument during class discussion. He is extremely capable of identifying inconsistencies in arguments, but is often more concerned with winning an argument than he is with finding the most rational explanation for a particular phenomenon.

Selecting students with diverse characteristics allowed a more meaningful comparison of their reasoning processes, including an analysis of whether such differences were the result of qualitatively and / or quantitatively different approaches to the construction of scientific meaning. When these differences were compared to the characteristics of very young children and field experts, it was possible to provide evidence for a developmental progression in students' thinking. It was also possible identify to more clearly the variables that may suggest different ways of thinking and varying degrees of ability within the identified stages. By identifying and analyzing specific differences among the children in the small group and using these differences as benchmarks for comparison with the larger group, a more detailed description of the nature of these differences was made possible.

The five students who took part in individual interviews were involved in an initial narrative interview and two think-aloud interviews that were based upon their continued development of arguments and ideas generated during class discussion. They were encouraged to reflect upon ideas and arguments developed during class discussion and during the individual interview itself. All of the students who took part in the individual interviews were well accustomed to a classroom context in which their ideas were valued and in which argument was encouraged. Because the intent of this study was to observe methods by which students generate and evaluate ideas, the identification of more and less productive means of doing so was able to be done without consideration of the impact that other personal or demographic variables may have had on these methods. Although the methods of meaning construction identified in this study are likely generalizable to other students of this age, the manner in which these methods manifested themselves in the classroom was likely largely influenced by the small class size and close-knit community in which the study took place. Further study would be necessary to determine how students' ideas could be elicited and challenged in a larger setting with students who were not as familiar with one another as were the students in this study.

A copy of the permission letter sent to the parents of students who participated in videotaped class discussions is provided in Appendix B.1, whereas the parents of the students who also participated in individual interviews received the letter in Appendix B.2.

### 3.2.2. Initial narrative interview.

As discussed earlier, teaching for conceptual change requires an understanding of students' prior experiences and understandings. To understand how students think as they construct scientific knowledge, it was important to develop an understanding of how their broader interests, passions, perspectives, and understandings related to the manner in which they did so. In an attempt to gain a glimpse into these areas of the students' lives, audiotaped narrative interviews were fully transcribed for thematic analysis. Because human minds do not always recognize boundaries created by labels such as "science," it was important that I understood as much as possible about the students and the factors that influenced their ideas. Analogies, by their very nature, draw on diverse cognitive frameworks. As has been noted by di Sessa (1983, 1988), Spiro et al., (1989), and Strike and Posner (1992), misconceptions, too, may be rooted in widely diverse areas. In light of these ideas, understanding what is important to the children, what they spend their time thinking about, and the manner in which they solve problems in their daily lives all assumed significance. As the students worked through various units in science over the course of the study, it was interesting to note connections between the nature of the analogies that they generated and the broader meaning-perspectives that emerged during their narrative interviews.

The questions used as starting points for the narrative interview are included in Appendix C.1. Probing questions were used as necessary to elicit more detailed information that appeared to be important to the students being interviewed. The questions were deliberately open-ended to allow the most natural responses from the students. Clearly, the same questions on different occasions could prompt different responses, but if a child has "a major preoccupation or organizing frame of reference, this would be likely to manifest itself one way or another on different occasions" (Ellis, 1998, p. 5). Obviously, it is not possible to develop an understanding of the totality of any child's mind. By becoming aware of major frames or themes, categories of ideas emerged that allowed an interpretation of the students' scientific thinking that took into account their broader frames of reference. Additional information of this nature was gathered informally throughout the course of the study. By conducting the formal interview, a more integrated perspective of the students' characters was gleaned than would have been possible simply through informal daily encounters with the children.

The students seemed to enjoy the attention of the interview, and it seemed to emphasize to them their importance to the research project. As Mishler (1986) stated, "If we wish to hear respondents' stories then we must invite them into our work as collaborators, sharing control with them, so that together we try to understand what their stories are about" (p. 249). Students in the regular classroom also responded very favorably to questions regarding their scientific ideas and thoughts. This is consistent with Weber's (1986) speculation regarding why people are willing to participate in interviews: "Perhaps one accepts to be interviewed because in the very invitation there is a sense of trust and a confirmation of the participant as a human being of importance, as someone who knows something of value, to research and science" (p. 67).

### 3.2.3. Classroom observation.

> *Science confronts the work of one man with that of another, and grafts each on each; and it cannot survive without justice and honour and respect between man and man. Only by these means can science pursue its steadfast object, to explore truth.*
>
> (Bronowski, 1964, p. 69)

*So long as the child supposes that every one necessarily thinks like himself, he will not spontaneously seek to convince others, nor to accept common truths, nor, above all, to prove or test his opinions.*

(Piaget, 1967, p. 53)

As the broad questions that guided the initial discussions of new topics were introduced and revisited throughout the three units of study, the ensuing discussions and activities that took place as students shared and debated their ideas were videotaped. Discussions of this nature often spanned full eighty-minute class periods, particularly during the electricity unit. During the chemistry unit, a conscious effort was made to ensure that the students limited their discussions to half of each class period. Without such an effort, they would typically keep talking until they had no time left for their investigations. They very much enjoyed their discussions, and they often continued to debate their ideas after the lunch bell rang and they were dismissed.

During class discussions, I operated the camcorder, asked questions, contributed arguments, and attempted to ensure that all of the students were given a chance to speak. The students quickly became accustomed to my position behind the camcorder and did not seem at all disturbed by this arrangement. My non-central position may have helped promote the student-student interaction that was prevalent during these discussions: On average, my comments comprised about 17% of the total number of comments, and a large portion of these were questions encouraging the students to elaborate or clarify their ideas.

Because it was impossible for all of the students to have the opportunity to share all of their ideas, I requested that they provide a written summary of their electricity experiments and battery models and that they maintain a journal regarding their ideas and investigations during the chemistry unit. In some cases, these provided small insights into the progression of the student's ideas, but they were generally a very limited source of information.

The decision to videotape the class discussions was made on the basis of the need to capture the gestures, demonstrations, and chalkboard drawings that the students often used to develop, evaluate, and communicate their ideas. In addition, one of the videos was used as a highly productive means of stimulating reflection pertaining to the features evident in the discussion that the students perceived as conducive or prohibitive to the ongoing development of the ideas being discussed. A second video was used somewhat less productively in an attempt to have the students determine the sources and types of the questions and arguments used during the discussion. Many of the reflections elicited in response to video-based reflection are included Section 4.2.

The remaining videos were transcribed, and the resulting transcriptions were coded and re-coded in ongoing cycles using software designed for that purpose. The categories used for analyzing the individual interviews were used and extended, and additional coding allowed the separate consideration of information gathered from different sources. The resulting categories are discussed in Chapter Four

### 3.2.4. Field notes.

Field notes were conducted in an attempt to document the manner in which students related their empirical observations to the theoretical questions that they were supposed to be investigating. These notes were based on observations of and discussions with students working in individual small-group settings. Due to the practical constraints of observing in this environment, they were limited to segments of each group's work, but did provide chronological summaries of the sequence of activities in which each student engaged. More general summaries are provided in Appendices D.2 and F.1. Theory development and evaluation continued as the students took part in the empirical investigations that were necessary to test some of the arguments that they generated. However, much of their mental energy during this time appeared to be directed toward the practicalities of setting up their equipment in a manner that allowed them to conduct their tests in a fair manner. Interpretation of results often took place during subsequent class discussion. Some students had difficulty relating their test results, or even the purposes of their tests, to the broader discussion and required considerable guidance during class discussion to do so. In other cases, the students were able to present results that were explicitly connected to the main question for investigation. Their differential ability to relate their investigations to the guiding question is a central focus of the developmental levels inherent in the "focus of inquiry" framework presented in Section 4.3.1.

### 3.2.5. Think-aloud / reflective interviews.

Because the course of the classroom discussion followed a trajectory determined by the ideas and opinions of many students, individual students' reactions could not be elicited for every response. By interviewing five students individually, a deeper understanding of the thought processes that took place in these students' minds was made possible. The students did most of the talking, but probing questions were asked to encourage them to reflect more critically on the explanations they were developing. This approach capitalized on some of the successes that Clement (1981, 1982, 1986, 1988, 1989b) experienced with the think-aloud interview. In addition, the interviews provided an important point of comparison regarding the students' use of identified strategies and evidence that such use was sometimes conscious or deliberate.

The personal interviews were conducted near the culmination of each of the units that formed the context of the study. During each interview, I asked each student to share his or her most recent explanation of either the battery or the vinegar and baking soda reaction. The student was then encouraged to identify questions that remained unanswered, and to attempt to resolve these questions. Although on-the-spot reflection tended to interfere with students' ability to think about the question and was therefore not encouraged in great depth, the students were asked to verbalize their thoughts as they worked through the development of their ideas. Sample interview questions are included in Appendix C.2. These were extended as necessary to elicit the desired information. The interviews were videotaped, fully transcribed, and thematically analyzed in conjunction with the transcriptions of classroom observations.

The students had access to the supplies used during the unit of study so that empirical methods could be used to test the implications of any ideas formed during the interview. This also allowed them the opportunity to confirm and / or demonstrate findings made on previous occasions if they so desired. The utility of making equipment available is evident in the following:

> One of the things which became obvious to us as we conducted the trials was how helpful it was to conduct the interview near where the children's graphs were displayed. Children frequently referred spontaneously to the graphs and also to the equipment when it was within reach. (Doig, Groves, & Clark, 1995, p. 5)

If a student was unable to generate a question, I posed one. Wherever possible, these questions were based on puzzles identified by other students during previous class discussions, and each interview was deliberately culminated with at least one unresolved question. At the end of their interviews, the students were asked to identify factors that had helped them to question or further develop their ideas and were asked to identify sources of good ideas and arguments.

Initial plans to use video-based reflection during the individual interviews were altered for three reasons:

1. Video-based reflection was an activity that worked well as a whole-class activity.
2. Observations of sustained thinking were deemed more important than observations of student reflections on dialogue from a previous day.
3. Caveats provided by Doig et al. (1995) were heeded:

> We had already made the decision to use the graphs in the interviews when, unexpectedly, we were not able to use the video player during one of the trials. The only options were to conduct the interview without the video-tape or to come back another day, which would have been extremely difficult. We decided to use only the graphs and the equipment as stimuli for the children. The interview was more informative and more relaxed than the previous ones. Unlike the previous situation, which had worked well only once, subsequent trials were also successful. (p. 6)

Rather than go through the cumbersome process of rewinding and fast-forwarding the video, and even then gain only retrospective perspectives on student thinking, first-hand observation of student thinking was deemed preferable. The reflections at the end of the interview were likely as detailed as any provided by video-based reflection would have been.

### 3.2.6. Research diary.

By combining analysis of the students with self-reflection and analysis, a greater understanding of students' scientific thinking was obtained. My research diary contained evidence of my own evolving thoughts and perceptions regarding how students learn as well as a reflective account of how I thought through a variety of scientific problems. Almost invariably, the phenomena that the students were investigating provoked seemingly endless questions of my own. These were sometimes different from the ones that puzzled the students, but they were helpful in generating deeper conceptual understandings of various phenomena. Analyzing the sources of personal questions and theories provided deep insights into how understandings of scientific concepts are achieved, how scientific understanding develops, the difficulty inherent in reflecting upon the sources of ideas, and the ways in which more fleeting and deeply implicit ideas may be captured and used more consciously.

The information obtained from the students was, at best, second-hand. Using personal thoughts and reflections provided a first-hand source of information. This helped confront the problem Nersessian (1992a) identified in her discussion of cognitive-historical analysis:

> The diaries and notebooks of a Faraday may be the closest we will ever get to "on-line" thinking, and even these cannot be taken as involving no reconstruction and as capturing all the shifts and strategies employed. If we can show, however, that what the particular scientist claims and / or seems to be doing is in line with what we know about human cognitive functioning generally, we can build a stronger case for our interpretation and fill in missing steps in a plausible manner.... (p. 36)

Studying students as they constructed meaning rather than trying to piece together ideas from the historical record also contributed to this process.

Finally, to understand how personal perceptions of learning color the views of student learning that I brought to the study, it was important that I maintain an explicit account of how it is that I viewed my own learning. At the same time that personal reflections aided my understanding of student learning, I needed to take great care to avoid the premature imposition of this way of learning on the students. This was very significant both in the analysis of the research data, and, ultimately, in the implications for teaching that emerged as a result of these analyses.

# IV. RESULTS

## 4.1. Introduction

The analysis of the classroom observations and individual interviews that formed the bulk of the data for this study took the form of a dialectic between inductive and deductive reasoning as new themes and sub-themes emerged, were tested against the data and for internal consistency, and were modified and re-evaluated in an ongoing cycle. New ideas that each time incorporated and transcended the old by building frameworks that were consistent and plausible were continually tested against the reality of the classroom. It is interesting how this process in many ways mirrors the one that it is describing. Its fuzzy pre-paradigmatic beginnings were exemplified by a search for methods of problem and solution, which at first were far from clear, and led to the gradual formation of a framework that provided an increasingly stable basis for formal analysis of the data. I have attempted to make this framework internally consistent in a manner that goes beyond a priori judgment. As new observational guidelines led to new foci for observation, analysis of field notes often left me wishing I had observed more carefully for criteria for which importance was not obvious at the outset. The transcribed interviews and class discussions proved invaluable in this regard. Finally, just as new understandings prompted new ways of searching and analyzing the data, they also prompted new questions of the literature. As a result, the review of the literature that began in Chapter Two continues throughout Chapter Four, and emerging ideas are frequently evaluated against work done by others.

Due to the self-reflective component of the study, the results that follow are written in the voice of the first person. It is my hope that this format will be easier to read and will be more indicative of the manner in which my own emerging knowledge frameworks guided the observations and insights that I present.

The results of this study are organized into three broad sections. Section 4.2, "The Evolution of an Effective Classroom Context," is primarily a chronological, narrative description of the units that served as the context for the study. In this section, the evolution of the guiding question(s) for each unit is discussed, and the types of behavior that characterized both student and teacher activity are summarized. My intent in including this component is not to suggest that the classroom or instructional environment that evolved is uniquely responsible for promoting the idea-generation or evaluation strategies that are analyzed in the subsequent sections. Rather, I use it to document the efforts taken to establish an environment in which such strategies could be made evident and therefore amenable to analysis. So saying, however, I grasped every opportunity of which I was aware to help the students further refine identified strategies and have attempted to identify critical aspects of this environment in Section 4.4 ("The Role of the Teacher") and Section 5.2 ("Implications for Science Education").

Section 4.3 forms the heart of the study. It is based upon a thematic analysis of interview transcripts, transcripts of class discussions, and field notes gathered as the students took part in individual or group investigations. Major themes are organized around students' general approach to inquiry (Section 4.3.1), their use of analogical reasoning (Section 4.3.2), and their ability to develop broadly applicable theories (Section 4.3.3). Students' understanding of and use of empirical procedures (Section 4.3.4) and communication strategies (Section 4.3.5) are then briefly considered. Within each of these categories, four developmental levels have been identified. In most cases, the students who took part in this study displayed either Level 2 or Level 3 criteria, whereas Levels 1 and 4 are primarily based on examples from the literature and on extrapolations of Levels 2 and 3 criteria.

Section 4.4 ("The Role of the Teacher") identifies specific ways in which my actions and comments appeared to impact the manner in which the students generated and evaluated their ideas. It incorporates ideas developed in the previous sections, but attempts to build a broader and more cohesive picture of the teacher's role. It, too, is based on a thematic analysis of the transcripts and field notes.

By focusing on the nature of the classroom context, the manner in which students formulate and interact with their own and others' ideas within this context, and on my role in facilitating the theory-development process, I have attempted the beginnings of what I hope will become a comprehensive picture of the factors that are most necessary to effectively facilitate students' construction of scientific understanding in an elementary classroom.

## 4.2. The Evolution of an Effective Classroom Context

*There are two aspects to providing occasions for wonderful ideas. One is being willing to accept children's ideas. The other is providing a setting that suggests wonderful ideas to children – different ideas to different children – as they are caught up in intellectual problems that are real to them.*

(Duckworth, 1996, p. 7)

The nature of the classroom activity encouraged as a context for this study was largely based on the ideas discussed in the literature review. Over the course of the study, it evolved continuously as individual students took (and were granted) increasing control of their own questions and investigations. Throughout both of the units upon which the study was based, the students were expected to act as members of a scientific community. They generated questions and ideas, presented them to the class, discussed and debated their validity, and performed experiments as necessary to test them. Many changes to the classroom context took place over the five-month observation period. Whenever possible, I tried to base changes in my own expectations and actions on factors that the students identified as necessary. Trumbull's (1990) goals for the students in her pre-service teacher education classes mirror mine very closely: "These changes may be slowed by my deep belief that, were I to give students explicit directions about how I wanted discussion to develop, these good students would mechanically mimic the behaviors I describe but not the intents" (p. 17).

The initial, broad questions that formed the basis for student investigation throughout the observation period emerged from introductory class discussions that took place at the beginning of each unit. During the electricity unit, experimentation and personal knowledge were the prime sources of evidence used for theory evaluation. For a large part of the unit, experiments were designed as a class, and groups of students conducted the same or very similar tests and then compared and discussed their results (as shown in the unit timeline in Appendix D.1). The students' battery explanations were much more individualized and provided a greater indication of individual tendencies and abilities, as did the class discussions that provided an important and thought-provoking environment for the discussion and debate of emerging ideas. Peer-review of ideas gradually led to more thorough self-questioning as the students reflected upon the nature of the activities and discussions in which they were engaged and as they learned to anticipate the questions and arguments that their peers might present. As both the students and I reflected upon legitimate sources of knowledge and ideas, the use of books and other reference materials became more prevalent in the second unit of study. Also, the students were given more freedom right from the beginning of the second unit, and a larger part of the responsibility for developing questions and investigations that would aid the development of a deeper understanding of the reaction between vinegar and baking soda was placed directly under their control. Peer-review of ideas continued to play an important role in the theory-evaluation process, but the students were encouraged to become more self-critical rather than waiting for others to provide arguments and questions to challenge their work. This approach led to much greater diversity of both type and sophistication of classroom activity. This is reflected in the amount of time dedicated to individual investigations in the activity timeline for the chemistry unit (see Appendix E.1). At times, the focus on individual investigations seemed to damper interest in whole-group discussion, but analysis of the more successful discussions yields insight into ways that this difficulty might be avoided. What follows is a brief chronological account of pivotal events that occurred during the five-month observation period. It is organized into three sections: The first pertains to the electricity unit, the second to a transitional period that involved a pivotal discussion about the role of books and outside sources of knowledge, and the third to the chemistry unit.

### 4.2.1. Investigating DC circuits.

> *There would appear to be a limited number of ways of making students aware of the role of experimentation in the development of scientific knowledge. It is essential that they personally experience the situation, but this obviously presents practical difficulties. How, for example, can a problem be devised that is within the capabilities of these young minds and that at the same time offers scope for experimentation?*
>
> (Nadeau & Désautels, 1984, pp. 49-50)

At the beginning of each unit, it was necessary to find a way to approach the important concepts in a manner that built on the students' interests and experiences. In each case, an initial discussion quickly made evident avenues for fruitful exploration and led to the development of questions that focused classroom activity for the remainder of the units. In the electricity unit, discussion began with a practical question. The students had just completed a project in which they had designed and built burglar alarms. During this activity, each of them built a model house, installed their alarm, and wired it in a manner that would cause an intruder to trip a switch that caused a bulb to light in a telltale location of the house. Several students noted that being in the wrong room at the time of an intrusion could result in failure to notice the lit bulb. Some proposed a loud buzzer in place of the light, and others suggested placing alarm bulbs in several areas of the house. Although the buzzer may in some ways have been a more practical solution to the problem, the problem of lighting multiple bulbs was more conducive to developing an understanding of different types of circuits, and proposals for the wiring of this alternative formed the impetus for an initial discussion of circuits with multiple bulbs.

As the students suggested ideas to address this challenge, they soon realized that there were a variety of possibilities that needed to be considered (see Appendix D.2 for a summary of the circuits they proposed). Samantha's solution involved three bulbs on three completely independent wires. Carl's, Rebecca's A- and B-, and Rachel's circuits were almost identical, although the students did not yet recognize this. Each displayed bulbs with uninterrupted paths to the battery terminals and differed from Samantha's only in that the paths to the battery terminals included some shared pieces of wire. New bulbs in Rebecca's circuit were added by connecting new leads to the posts of the bulb holders, and her A- and B-circuits differed only in terms of which bulb post the wires were connected to (she was unsure whether bulbs have polarity). Rebecca's B-circuit was actually identical to Carl's circuit, although neither she nor any of the others realized it at the time. Rebecca's C-circuit was a basic series circuit. Frank's A-, B-, and C- circuits were very similar to Samantha's circuit except that each used two cells. In his diagram, these appeared to be connected in series, but actually had individual connections to each cell, thereby creating short circuits. Most of the students rightly asserted that Frank's D-circuit would not work, because he connected the cells from one positive terminal to another. Finally, as Robert pointed out, Frank's E-circuit was essentially three separate circuits, each with its own cell.

As the students drew their circuits and questioned each other for clarification, the need for a method to show which wires were actually connected and which were just passing over one another became evident, and their circuit diagrams were modified to show wire jumps (little bumps in the wires at points of crossing). Throughout this questioning period, the students' questions exemplified a search for the salient features in each of the circuits. It became apparent that Rebecca's B-circuit was actually a mistaken redrawing of her A-circuit, but the debate over their proposed similarity included an in-depth discussion and subsequent investigation to determine whether bulbs have a positive and a negative side. This included testing the effects of reversing the connections to a fan, a flashlight, and a bulb. Reversing the connections on the flashlight involved further analysis of the role of the battery-chamber in the flashlight, which the students eventually bypassed because it only allowed the battery to be inserted one way. The students also questioned whether shared wire was an important difference between Samantha's, Carl's, Rachel's, and Rebecca's circuits and considered the possibility that uninterrupted access to both terminals of a battery might be sufficient consideration for similarity. Frank's first four circuits evoked a good deal of skepticism. Many students doubted whether they would work at all. Robert's identification of Frank's last circuit as nothing more than three separate circuits was also an example of an attempt to identify salient features.

As the class was discussing different circuit types, Robert and Jennifer raised practical queries regarding how many bulbs a single battery could light, how the number of bulbs would affect the life of the battery, and how the number of bulbs would affect their brightness. Discussion of these matters further emphasized conflicting views regarding the nature of current flow as the students found themselves arguing from different premises. These disagreements provided seeds for what would later become a very involved discussion centered around the manner in which a battery functions.

Prior to encouraging further discussion of the circuits, I gave each student a copy of the sheet entitled "Thinking about Thinking" (Appendix D.3) with the hope that it would encourage them to reflect on the sources of their ideas as they continued to debate them. An interesting discussion based on sources of ideas ensued, but no clear connection between this discussion and subsequent reflection is apparent. Most of the students' comments focused on ideas that seem to appear suddenly and for no apparent reason and on how one idea can lead to another, then another, and so on. Carl mentioned that this process was sometimes distracting, and Jordan commented that sometimes this process "leads everybody else off track, too" (Class Discussion, January 9). It is interesting that four out of seven examples suggested by the students during this discussion were triggered by television shows or commercials.

As the students resumed their discussions of the circuits they had designed, they began to note more similarities between them. Samantha noted that Carl's circuit was really just a top view of Rebecca's B-circuit, and after carefully following the wires from point to point, the class indicated general agreement on this point. Once the students started to recognize the way the diagrams could mask similarity between circuits, I had them untangle all of the circuits (i.e. draw them without wire jumps), and many indicated surprise that so many of them were alike. Some claimed that Samantha's, Carl's, and Rebecca's A- and B-circuits were all alike, whereas others maintained that Samantha's was unique in that each bulb had its own set of wires to connect it to the battery.

Matthew and Frank argued about whether Frank's A-, B-, and C- circuits were alike. Frank insisted that they were not, because the wires were touching each other in some cases and only the battery terminals in others. Matthew maintained that this should not matter, because the current could just go through the metal. At this point, Robert asked a question that significantly affected the remainder of the unit: If the current is able to go through metal, why doesn't the battery short-circuit itself? As far as he could see, the positive and negative terminals were already connected by a solid piece of metal. A discussion of the possible structure of a battery ensued, and groups of students began to develop pictorial models to help determine how batteries might function. Following this day's discussions, I directed the students' attention to a handout on circuit diagrams, and we briefly compared their new drawings to the method shown on the handout.

Prior to continuing with the proposed circuit investigations, I had the students complete a written test that involved untangling circuit diagrams, predicting relative bulb brightness in various circuits, describing the function of a bulb and bulb-holder, interpreting various mechanisms that used different types of electrical switches, and drawing and explaining how they thought a battery might work. This allowed me to see which students in fact understood the concepts that had formed such a large part of the class discussions to this point and provided an opportunity for individual students to consider more deeply their ideas regarding the manner in which a battery functions.

Following this, I had the students refocus on the three questions that Robert and Jennifer had posed: (a) How many bulbs can you light with one battery?, (b) How does the number of bulbs connected to a battery affect how long the battery will last?, and (c) How does the number of bulbs attached to one battery affect the brightness of the bulbs? To help the students focus on what observations would be necessary to answer these questions, I had them use spreadsheets to design data tables in which they could record their data. Most of the students decided to indicate bulb brightness with descriptors such as "dim," "bright," and "very bright." As I questioned them about the difference between these categories, the need for a method of measuring brightness became apparent, and I helped them develop light-meters that would indicate varying brightness according to the number of layers of paper a bulb could be seen through.

As some students completed this task and were waiting for the others to finish, I had them question each other's battery models, which were relatively simplistic at this point. I instructed them to provide written feedback to each other in the form of questions and arguments, and they very enthusiastically undertook this task. The entire class became very interested in this activity, so I photocopied each student's model enough times that each student had a copy of every other student's work. All of the students participated in the written evaluation of each other's ideas. They were highly motivated to share and debate their ideas with their classmates, and the activity quickly grew into a fast-paced written dialogue. Some of the arguments were very well thought out, and some were simply argument for the sake of argument, but the positive response to this task set the atmosphere for the enthusiastic large-group discussions that followed.

When discussion returned to the circuit-testing that had prompted these debates, the students' convictions about the differences between the various proposed circuit-types made obvious the need to control the circuit-type as they conducted their tests. There was widespread disagreement regarding whether Carl's and Samantha's circuits were alike, and it quickly became obvious that differing views about the functioning of a battery and about how current flows were at the heart of the disagreements. Some students used the idea of two different substances that crashed in the light bulbs, whereas others favored a single, unidirectional moving substance. Implications for views pertaining to the nature of energy, the fate and / or existence of used energy, the possibility that positive and negative particles could mix in the battery rather than the bulb, whether batteries actually have dividers, and possible differences between new and used batteries were all incorporated into increasingly sophisticated arguments that the students frequently supported with empirical evidence. Many of their arguments directly confronted classical misconceptions regarding the nature of current flow (R. Osborne, 1983, Shipstone, 1984), and the resolution of these issues became prerequisite to meaningful discussion of the circuits. Their arguments are presented in greater detail in Section 4.4.1 and Appendix D.4.

At my suggestion, we decided to test all three of the circuit-types that the students still considered both unique and functional: (a) Carl-style (bulbs in parallel with some pieces of shared wire), (b) Samantha-style (bulbs in parallel, but with no shared wire), and (c) Rebecca (C)-style (bulbs in series). Some students were convinced that different bulbs within the same circuits would vary in brightness, and Rachel suggested numbering the bulbs so that these differences would be evident in their written observations. The numbered diagrams are included in Appendix D.2.

After the students completed their circuit-tests, they analyzed their data for patterns, and were asked to identify observations that did not make sense according to their theory of battery function / current flow and to elaborate upon and modify their models as necessary. Part of this process included reaching an agreement about the amount of apparent difference in brightness that may have been due to observational error. Although the results demonstrated some definite overall trends, they were not entirely consistent. This ambiguity likely reinforced the tendency of many students to identify as accurate those observations that supported their own views. This is discussed further in Section 4.3.4.3.

After these tests, discussion of different battery models resumed, beginning with Frank's presentation of his crashing-current model. Many detailed arguments were raised, and after the students debated his model for approximately one-and-a-half eighty-minute class periods, I asked Andrea to present her one-way current model. Andrea represented energy as something that was used up as it passed through a bulb. Again, many interesting arguments were presented, and many unresolved puzzles remained when I finally pulled the discussion to a close.

As a culminating activity, I presented the students with a written summary of the models that had been discussed. This included a summary of the unsolved puzzles that remained for each (see Appendix D.4), and the resulting discussion centered primarily on the implications of divided vs. undivided battery models. This led back to a discussion of the nature of energy, and the students consulted a variety of reference materials to try to explain the role of electrons in electrical circuits (this discussion took place after the debate on the role of books that is discussed in the following section). The final discussion left the students with many unanswered questions regarding both one-way and two-way models of current. The value of these questions as catalysts for later learning is discussed in Section 5.1.2.1.

The students' inability to develop a consistent premise from which to argue their understandings of the different circuits seems to exemplify pre-paradigmatic science: "The pre-paradigm period, in particular, is regularly marked by frequent and deep debates over legitimate methods, problems, and standards of solution, though these serve rather to define schools than to produce agreement" (pp. 47-48). Certainly, the problems associated with a two-way current model were quite different from those associated with a one-way model, as were those associated with a divided vs. an undivided model. Different problems were also associated with different perceptions of the nature of energy.

Throughout the electricity unit, the majority of the activities were identified by one or more of the students and subsequently conducted by the entire class (working in small groups). As a result, the ideas of the more vocal and / or those quicker to propose ideas guided the progression of activities that took place. However, all of the students took part in the arguments and stayed remarkably attentive throughout the lengthy class discussions that occurred during this unit.

### 4.2.2. Reflections on classroom discussion.

As the electricity unit drew to a close, I showed the students a video of one of their discussions and invited them to compose a written list of elements of discussion that seemed to help or hinder the progression of ideas. The following day, they shared and discussed their ideas and developed a list that was supposed to reflect a synthesis of all of their contributions. Frank and Andrea acted as transcribers during this activity and were responsible for writing down (on the chalkboard) each of the ideas suggested by class members. Sometimes they paraphrased the ideas to make writing them more manageable, but they shared responsibility with those presenting the ideas for ensuring that original meanings were maintained. If students appeared hesitant or unsure, I occasionally stepped in to help them clarify intended meanings. The following excerpt is typical of the dialogue that took place during this discussion:

> Samantha: Frank, you just had that on the board right there.
>
> Frank: What?
>
> Samantha: "The same question twice."
>
> Frank: I know.
>
> Samantha: That's not what I said. I said, "the same questions all in a row."
>
> Frank: Okay. The same question twice. I'm saying, "the same question twice."
>
> Ms. S.: But Samantha's is different. Listen carefully.
>
> Samantha: I said that, um, people would ask questions all in a row. Like four questions in a row.
>
> Ms. S.: Not the same question.
>
> Samantha: Yeah, not the same question.
>
> Frank: Okay. "Keep on saying questions without getting answers."
>
> Ms. S.: Does that say it Samantha?
>
> Samantha: Yeah. (Class Discussion, March 16)

When the students focused on very particular details, either I or one of the other students attempted to elicit or formulate a more general statement:

> Ms. S.: Okay. I think you're on, Matthew.

Matthew: Okay. Finding that bulb. Like, they just ran, and they were looking for that bulb, and they couldn't concentrate on the sentences that they were saying, mostly because they were too into finding that bulb.

Frank: So doing different things?

Matthew: Yeah. That'll say it.

Carl: Too many people looking for the bulb.

Matthew: Yeah, okay.

Ms. S.: So which one do you prefer? Frank said it one way, and Carl said another. Which one do you.... How would you like it worded?

Matthew: Um, Carl's.

Ms. S.: Is it just a bulb problem, or is it a bigger problem?

Matthew: Well they were just looking for the bulb, and everybody was talking. And then while they were going, like, most of the people couldn't hear the sentences they were saying.

Ms. S.: Okay. So do you want to put.... Do want to say it's about the bulb? Or do you want to do what Frank did and say, "Don't do other things while you're arguing"?

Samantha: I think Frank's way, because batteries, too, when they were testing, like, everyone went and got different batteries and stuff to test.

Frank: Or just say like this: "Too many people doing different things." Class Discussion, March 16)

At the end of the class, I gathered the lists that individual students had compiled while watching the video and added any points that appeared to have been omitted during the class discussion. During the following class, I distributed this list (Appendix F.1) to each student. I asked each of them to read it and to comment on any items about which they were unclear or with which they disagreed. The points added after the class discussion were indicated by bold print, and I drew the students' attention to these to be sure that they were carefully considered. Following this discussion, most items remained the same, but a few were elaborated for clarification. The modified list is included in Appendix F.2.

Many of the students' reflections focused on the nature of interaction within the classroom and on the communication skills used by class members as they shared their ideas, but other factors that dealt more specifically with the use of ideas and arguments were also identified. The role that books should play in the idea generation and evaluation process was heatedly debated in a discussion that consumed an entire eighty-minute class period. Points relating to each of these categories are discussed in the following section and are further elaborated in the discussion of the chemistry unit that follows in Section 4.2.3.

#### 4.2.2.1. Classroom protocol.

In terms of basic conversational protocol, the students identified three major points as important: (a) "cooperating to take turns," (b) "putting up hands and jumping in", and (c) "10 sec. or 5 sec. rule for jumping in." Many of the students were opposed to having to put up their hands, because they felt it interrupted the train of their arguments. However, some indicated that they had a very difficult time jumping in, and preferred to put up their hands. The resulting compromise was an agreement that it was not necessary to put your hand up prior to speaking. However, if you were having difficulty breaking into the conversation, you should put your hand up, and the other class members should recognize and respect this request by inviting that person into the discussion at an appropriate point in the dialogue. This applied to me as well: They identified "Ms. S. jumping in with questions" as a positive feature of discussion, but were critical of my intrusions in other instances. Several students recommended the use of an idea page on which they could write down ideas that they wanted to share so that they would remember them when an opportunity arose, and several students had already made good use of this strategy. The "10 sec. or 5 sec. rule for jumping in" was introduced in response to Carl's concern that "If you are pausing for about two seconds or something, and somebody jumps in, and you're just thinking of another way to come at so the other person understands it, then you feel kind of like 'Hey, I was talking. I'm not finished yet'" (Class Discussion, March 16). The actual amount of necessary wait-time was debated, but there was general agreement regarding the need to make sure that the last person speaking had not just stopped to think.

#### 4.2.2.2. Clear communication.

The students identified quite a number of points that focused on clear communication. They appreciated examples, diagrams, and "action explanations," which Samantha defined as "using your own body" to help communicate. They noted that "testing things" was helpful, but complained that "props" sometimes got in the way and would be more helpful if used where everyone could see them. They claimed that "too many people doing too many things" was distracting, and were also critical of "talking to yourself." Andrea's and Samantha's identification of questions that could be shared by everyone seemed to play an important role in effecting a transition from a confrontational approach for challenging each other's theories to one that was more cooperative:

| | |
|---|---|
| Andrea: | For what didn't help. Like some people would ask questions, like, that would occur to almost everyone. So, don't ask them specifically. Just ask them to the whole class, not to one person. |
| Samantha: | Yeah, like that energy question. That was sort of like everyone's question. What is energy? |

Ms. S.: Okay. So some things, we are all puzzling over. Yeah, and did you feel attacked when people directed it directly at you?

Andrea: Yeah.

Ms. S.: Okay. So, it's not like you haven't explained energy. It's like, could we all work to explain energy. (Class Discussion, March 20)

The students agreed that it was important to support each other's ideas rather than always arguing with them and that certain questions with which they were all struggling should be directed toward the whole group rather than solely at the person presenting at that time.

#### 4.2.2.3. The value of argument.

Some of the points dealing with ideas and arguments tended to be quite general and served mainly to point out the value of argument, whereas others were more indicative of specific argument strategies. The students' identification of points such as "arguments bring out more things," "lots of questions," and "new ideas" (ideas that emerge from large-group sharing) as useful indicate their growing awareness of the role of debate in scientific knowledge construction. By recognizing the value of this type of dialogue and recognizing the types of social and communication skills necessary to make it effective, the students demonstrated important understandings about the nature of science and the manner in which scientific understanding develops. Their recognition of the importance of using previous arguments (rather than starting over each time), "staying on topic," and "staying on one battery" demonstrate their understanding of the need to concentrate on a given topic to gain a deeper understanding of it. In a related vein, their identification of "keep on saying questions without answers" as a negative feature of discussion emphasizes the need to allow the person being questioned to have time to think about a single question before being bombarded with a whole series of them. Finally, Robert indicated concern with what he viewed as poor ideas or arguments suggested only as a means of saving a theory:

> Robert: Well, some people, they would have an idea, and they would say their idea, and then they had to.... The person would argue it, so they would just make something up off the top of their head, and it would be something that wouldn't make sense. So just saying anything.
>
> Ms. S.: Just saying anything. You mean anything just to save your theory?
>
> Robert: Yeah.
>
> Jordan: It's just nonsense.
>
> Samantha: It doesn't save your theory then.
>
> Robert: It's like you're just trying to chuck something in until you can think of something good enough. (Class Discussion, March 16)

Robert's concern appears to identify the phenomenon referred to as "ad hoc hypothesis" in the literature pertaining to philosophy of science (T. Kuhn, 1970, p. 78).

Jennifer's growing understanding of the importance of admitting when you don't really understand something is evident in the following dialogue:

> Jennifer: Sometimes your own knowledge doesn't work. Let's say you've thought of something, and then you say it all, and then they argue about it. You think you have it all planned, but then after all the arguments, it doesn't work.
>
> Ms. S.: So, you mean that your original idea might not always work? Is that what you're saying?
>
> Jennifer: Yeah.

> Ms. S.: And so, what's your suggestion then? So, is that a bad thing when your thing doesn't work, or....
>
> Jennifer: It's a good thing, 'cause then you can learn more.
>
> Ms. S.: So, how do you want to put this?
>
> Jennifer: Well, it can go on both ["Helped" and "Didn't Help"], 'cause sometimes you think you have it all, but you find out it doesn't work, but then it can be good because you can learn more about it.
>
> Ms. S.: So, is it okay to change your ideas then?
>
> Class: Yeah.
>
> Ms. S.: So, it's good because what?
>
> Jennifer: It's good because, like, maybe, you're not really sure about it, but you think you have it all planned out, and then when you argue it and you can't find anything out, then maybe finding out new things about your idea is good.
>
> Ms. S.: Okay. So, arguments bring out new things?
>
> Jennifer: Yeah.
>
> Ms. S.: Okay. (Class Discussion, March 16)

During the following class period, Andrea questioned Jennifer further on this matter, and her clarification of the point emphasized her understanding of both the value of argument and the need to avoid ad hoc responses:

> Andrea: For "Didn't Help," for sixteen: "Sometimes your own knowledge doesn't work." What does that mean?
>
> Ms. S.: I think that was yours [pointing to Jennifer].
>
> Jennifer: Well, you know when you like, um, have everything planned out. Like, you have your battery, and the stuff that you're thinking of, everything that you want written down, and it's all you can think of. Well then people ask you.... Say Robert asks you one of his really tough questions, then you try to answer it, but it just doesn't make sense with your own knowledge on what you have.

Samantha: I think something like that, what Jennifer said, but like, your own knowledge. Like when Robert asks a question or something, and you try and answer it, and you just want to answer it. Like you don't have an answer, but you just answer it with whatever words you have. So it doesn't really make sense. Sort of like that. Like, just say, "It goes through this wire" or something, so your answer doesn't really make any sense.

Ms. S.: So what should you do in a case like that? What is your suggestion here?

Samantha: Maybe you should.... Like, if somebody asks you a hard question, maybe, like, before taking any more questions, think about it for a while or something. Like, don't just try and give an answer back really quick.

Jennifer: Like say, "I'll get back to you on that."

Samantha: Or write it down or something so you can do it later.

Ms. S.: So, is that what you meant by that, Jennifer? Don't just jump in with anything. Admit when you don't know? Is that what that means?

Jennifer: Yeah.

Ms. S.: So, how should I write that? I'll just.... I'll reword it so that it makes sense. How should -

Jennifer: Well, if you can't answer a question, just say, "I don't know that."

Robert: Think before you answer.

Ms. S.: Is "Think before you answer" a different one?

Samantha: Yeah.

Ms. S.: So, can you say, if you can't answer a question -

Jennifer: I'll get back to you on that.

Ms. S.: So, it's okay to admit if you don't know.

Samantha: 'Cause then if people laugh at you when you say you don't know, it's not your fault. It's their fault, 'cause they're being mean and ignorant. (Class Discussion, March 30)

Jennifer used her own strategy in the following discussion, and she paraphrased the questions and responses evident in the dialogue below in her journal. Although she did not reach any conclusions as to what the strange gas might be, she did make a serious effort to think about the question:

Andrea: Why do you call the gas "strange"?

Jennifer: Well, um. We don't really know what it is, so it could be strange, couldn't it? Like if you didn't know what it was, and you said it's a gas, you wouldn't know that it's strange or not, would you? That doesn't sound right! Can I get back to you? Okay. Jordan? (Class Discussion, April 22)

Matthew also expressed a very clear understanding of the value of argument:

Matthew: Um, when we ask questions, everybody gets them, and then they think of questions, and then people get answers from them, and then more people think of questions from the answers, and then the argument goes on again. (Class Discussion, March 24)

#### 4.2.2.4. The role of books.

In a discussion that stemmed from the discussion of the things that did and did not help discussion of ideas, the students heatedly debated the role that books and other reference materials should play in figuring out how a battery functions. They agreed that "using your own knowledge" was important, but became very divided over whether "dictionary" should remain on the helped list (Class Discussion, March 30). The resulting discussion focused on books in general and involved many arguments about legitimate sources of knowledge. By the end of the class, nobody claimed that books had no value, but the students remained very divided on the role that books should play in their own idea-generation and evaluation. It seems that this was at least partially a reaction to the extreme position adopted early on by Robert that all information is located in a book somewhere, and that all we really need to do to learn new things is find out where. A somewhat shaky and directed consensus was achieved at the end of the class:

Jordan: How did they find out how to make paper? Because the books need to have paper.

Samantha: They try it.

Carl: Paper wasps.

Jordan: Do they go and watch a paper wasp?

Carl: A paper wasp would bite off the bark of a tree, and it would chew it up, and there is something in its saliva or something that will hold it together, and then it will spit it out.

Jordan: But how did they know what's in their saliva? How did they study it?

Samantha: They did tests.

Ms. S.: So, can we learn stuff from testing things?

Class: Yes.

Ms. S.: Can we learn stuff from looking at things?

Class: Yes.

Ms. S.: Can we learn stuff from books?

Class: Yes.

Ms. S.: Should we use all of those, or should we leave books out? The question is, "Should books be on this list?"

Class: Sometimes.... Yes.... Maybe....

Robert: So then, it's saying that we can't use books sometimes, so we shouldn't be able to use our eyes sometimes, so we shouldn't be able to argue sometimes.

Jordan: Okay, we're sleeping. We go like this [pretending to sleep]. We aren't using our eyes.

Ms. S.: Okay, but is that when we're trying to figure something out? You guys said that books are a source of information. Our eyes are a source of information. Testing things is a source of information. Should we leave any of those out?

Class: No.

Ms. S.: So, should books be on this list or not?

Carl: They should, but only if you absolutely need that type of information. (Class Discussion, March 30)

Although some points of agreement were reached during this discussion, the debate continued. The sarcastic comments are indicative of the conviction with which many students argued their points. By this time, some were becoming frustrated. At the beginning of the following class, all of the students agreed on a baseline premise that books could be useful in some instances. As a result, printed material was made more readily available for the culminating discussion of the battery as well as for the entire chemistry unit. For the most part, this was not required reading, but served as a source of information to help answer specific questions that presented themselves during the course of investigation and theory development.

Some of the issues addressed in this conversation go to the very heart of defining science education. It is not surprising that the students had difficulty resolving them. In the end, the decision regarding whether to use books was left largely to individual students. There were two instances during which I insisted that all of the students sit down and spend some time going through the printed material that I distributed to them, but I did not assign specified pages. Robert used books to a greater extent than did some of the others, but he had many questions about the material he was reading and still chose to conduct experiments of his own. During class discussions, all of the students were further exposed to information in books when the students who found valuable information in them had the others refer to certain pages to help clarify points that they were trying to make.

The students who used books typically did not find definitive answers to their questions, but they did incorporate pieces of information that they gleaned from their readings into their ideas in much the same manner that they incorporated observations from empirical tests. Here, the line between the context of development and context of justification vanishes. The students' theories were developed in their attempts to explain and justify their observations, including those presented as facts in textbooks. Complete answers to the students' questions were typically not found in the printed information. In this light, textbook information may be viewed as just one more source of information that needs to be accounted for in the explanatory framework of a theory. Furthermore, just as certain observations are only made once a theory drives the need to look for them, textbook information only became relevant at points in the theory-development process when it answered pertinent questions. An extended dialogue that demonstrates the students' interaction with textbook material is provided in Appendix G. The manner in which students made use of print material also has implications for the nature and timing of information presented to the students by the teacher, and these are discussed in Section 4.4.4.

### 4.2.3. Investigating the chemistry of vinegar and baking soda.

I initiated the chemistry unit by simply asking the students, "Anybody know what chemistry's about?" (Class Discussion, March 25). Matthew replied, "Where you usually take some chemicals and you mix them to see what happens." Robert agreed. Carl expanded the definition so that it became "mixing two or more chemicals to make something different." Samantha did not offer a general definition, but suggested that "Maybe an example of chemistry or something would be, um, vinegar and baking soda," and went on to explain that the "fizz" produced by their interaction indicated a chemical reaction. Robert attempted to generalize her example by saying that the interaction of the two substances was a chemical reaction, because "Something happens when you mix them together." The students continued to add descriptions of their encounters with vinegar and baking soda, and whether through their experiences with baking, cork popping, or volcano-watching at Science Fair, all indicated some level of familiarity with the reaction. I then challenged the students with the following: "Okay. But what happens? If you had those super-magnifier eyes, what would happen?" With this prompt, Robert generated a battle analogy that suggested the two chemicals "don't like each other, almost," and Keith proposed a bacteria vs. medicine analogy. Samantha suggested that when vinegar and baking soda meet, they "create a whole new thing," and identified "fizz" as the new substance. Rachel built on the battle analogy by comparing the chemicals to "two big men." Andrea related the reaction to the batteries they had studied in the previous unit: "When two acids mixed they made energy." Robert then elaborated the battle analogy to explain the gas production, claiming that the two chemicals could be fighting to release the air that exists between them. After this brief introductory discussion, I suggested that the students actually mix some baking soda and vinegar and watch it react so that they could attempt to draw what was happening, "kind of like at a Magic-School-Bus level."

During the next class, I had the students spend some time going through the reading material I had provided for them, partly to ensure that they at least familiarized themselves with what was available. As they were reading, they developed preliminary explanations of the reaction and one by one came up with ideas that they wanted to test. They gradually spread out around the classroom to conduct their investigations. During subsequent classes, activity alternated between conducting investigations and sharing and debating results and explanations. In summary, once the initial, general question was established, each student investigated his or her own questions and theories while remaining accountable to the larger group by reporting back each day.

The level of independence required in this setting was significantly higher than that required for the electricity unit, during which the students usually conducted similar tests that were based on puzzles identified during large-group discussions. The only constraint placed on the nature of the students' investigations was that the activities they selected were expected to help them develop a better understanding of how the vinegar and baking soda reaction takes place. As is discussed in Section 4.3.1, this constraint was met with varying degrees of success. The most significant developments that occurred within the evolving classroom context during this time period were the increasing level of collaboration that became evident over the course of the unit and growing tendency of the students to question their own ideas rather than waiting for others to challenge them. In fact, the tendency to self-question helped increase collaboration in that it encouraged students not only to admit but also to seek actively gaps and inconsistencies in their theories and to share these along with their theories.

#### 4.2.3.1. From competition to collaboration.

On the first day set aside for the sharing of results, Matthew asked enthusiastically, "Can we argue?" His question reflected the generally positive reaction of the class to this type of activity, and argument played a vital role throughout the sharing sessions that occurred during the chemistry unit. At the beginning of our April 20 class, I asked, "Are we looking to win or are we looking for the best answer?" The chorus of responses indicated that the students agreed that finding the best answer was the most important feature of argument, and their actions were usually consistent with this. This is also consistent with comments made during the earlier discussion of factors that helped and hindered classroom discussion.

In a number of cases, the students actually challenged each other's intents when they felt that someone was arguing for the wrong reasons. Usually, these challenges were directed at Robert. Although his competitiveness and his exceptional ability to point out gaps and inconsistencies in others' ideas often drove excellent arguments and questions, his approach to challenging his classmates' ideas was also at least partially motivated by his desire to prove them wrong. Robert's questions were usually legitimate, but his interrogative approach sometimes discouraged his peers from collaborating with him. Jennifer was the first to express concern with his methods. In the example presented below, Keith went one step further than Jennifer's "Why-bother-if-nobody-knows?" challenge and thereby encouraged the others to continue the discussion in a productive manner:

Frank: Well, I've got an idea. When the vinegar and baking soda mix, like, the baking soda is on the bottom, and then you pour the vinegar on, right? And then they mix, and all the gases.... The air bubbles will take the gases up and then release the gas.

Robert: Yeah, but where.... How does the vinegar and baking soda make the gas?

Frank: When they mix together.

Robert: Yeah, but what do they do when they mix together?

Frank: I don't know. They make gas.

Robert: When they mix together, how are they making the gas?

Frank: They're just mixing together, so there's a chemical reaction. Yeah, it's a chemical reaction.

Robert: What is the chemical reaction?

Jennifer: Do *you* know what a chemical reaction is?

Robert: Uh.... Kind of, but I -

Jennifer: Well, we can't argue about something we don't really know about.

Robert: Well, you can't just say, "It's a chemical reaction," because, like -

Samantha: How is it a chemical reaction?

Robert: Yeah. How is it a chemical reaction?

Samantha: What makes the chemical reaction?

Frank: Yeah, 'cause it reacts to the mixing.

Robert: So then why does it make a gas?

Keith: I have to figure that out before I can figure out what it does.

Frank: That's what I always try to figure out, too.

Robert: Yeah, me too.

Ms. S.: It's a puzzle, isn't it?

Keith: It has something to do with carbonate. (April 20, Class Discussion)

Keith's final comment prompted a more cooperative effort to find a solution. His admission that he, too, was struggling with the question being debated and his willingness to share his starting point for approaching it encouraged others to join in the effort.

Near the beginning of the next class, I anticipated further discussion of the "But-what-makes-gas?" issue, and I attempted to preface the discussion in a manner that I hoped would minimize feelings of antagonism or being picked on:

Ms. S.: No questions left over from before? Okay. With Rachel's, what were the main questions that people were asking? Do you remember? What did people ask about last day? Robert?

Robert: Where did the gas come from?

Ms. S.: So, people said, "Where did the gas come from?" "How is it made?" Is that arguing with Rachel's theory?

?: No, it's pretty much asking everybody.

Ms. S.: Okay, and so was it.... What were you asking Rachel for? Were you saying, "I don't agree with your theory"?

Robert: I was asking.... I pretty much agreed with it. I wanted to know where the gas comes from.

Ms. S.: So maybe more information?

Robert: Yeah. (Class Discussion, April 22)

As expected, Robert continued to pursue his line of questioning. Jennifer attempted to explain her ideas, and he continued to ask how and why the gas was made. The rest of the class eventually became frustrated with his persistence, and the following dialogue ensued:

Robert: How does the vinegar and baking soda mix to make a gas? How does that make a gas?

Carl: Can I say something? Don't ask questions that you yourself cannot answer.

Robert: I can answer that one.

Jordan: Okay, then, answer it.

Carl: And if you know it, why are you asking it?

Robert: Because they don't know it.

Samantha: Jennifer's trying to explain to you how the baking soda and vinegar makes the gas, but you keep saying, "How?" and "Why?" You won't let her answer. [In fact, Jennifer had attempted to answer many times, but was not addressing the how- and why-questions that Robert was pursuing so intently].

Robert: When they mix, what does that do? That doesn't help me. They mix to make a gas. Oh well, what does mixing it do to make a gas? When my sister fights me, I don't make gas [Here, he is alluding to an earlier comment by Jennifer that vinegar getting mad at baking soda is like getting mad at your sister for cutting your hair off].

Samantha: But those are chemicals. You and your sister aren't chemicals.

The discussion resumed for some time as the students generated and evaluated analogies pertaining to beans in your stomach producing gas, lava hitting water, and lava eating metal. Robert responded to this lengthy discussion with, "That doesn't help me. I want to know how you get gas." At this point, I intervened:

Ms. S.: Can I ask you guys a question? This is kind of related to what Carl said, and I'm not saying that you shouldn't, Robert. I'm just asking.... Maybe we can all come to a conclusion on this. Carl said that if you already have an answer, why ask.

Robert: Because I want a better answer than what I've got.

Ms. S.: Okay. Now, what do you think? Should Robert keep asking questions, or should he step in with a suggestion, or what would be the best? If we're looking for an answer here....

Rachel: Well, Carl said to only ask questions that you don't know. Well, maybe you already know the answer, but you're trying to get them to -

Robert: Realize it.

Rachel: Yeah.

Ms. S.: You want to know.... You haven't heard their whole theory, because they haven't explained that part of it yet. Okay, now does it sound like Jennifer has an explanation for that yet?

Frank: I think Robert should step in and say his idea and help Jennifer out, and then we get a little bit farther down the line. And then people should say their problems about Robert's idea of gas and then we could get even farther down the line.

Ms. S.: Should Robert jump in with his idea right away, or should he ask Jennifer first, or how should we do that?

Frank: He should let Jennifer finish what she's doing and sort of pause.

Ms. S.: And should he ask her first how she would explain it, or should he just say, "Well, this"?

Samantha: He should let Jennifer explain her idea and then ask questions after, 'cause we seem to be.... Jennifer's been trying to explain her gas over and over again, about six times, and she gets halfway through, and Robert says, "Well, how, how, how?" And Jennifer can't seem to.... I haven't heard the end of the story yet.

Ms. S.: So, shall we hear the end of the story?

Class: Yes.

Jennifer then discussed the changing smell that is evident as the reaction proceeds, and the class debated her ideas. Robert responded with, "That still doesn't tell us how the gas is made." Jennifer attempted to elaborate. Frank repeated his invitation to Robert: "Okay, Robert, show your idea." Although Robert's explanation did come closer to explaining how the gas is made, it left many questions unanswered, and these were immediately pounced upon by his frustrated classmates. The debate continued for some time, with Robert now taking an active part in the idea-construction process rather than just questioning the others.

Student monitoring of the intent of others' questions continued in later dialogues. Samantha was particularly effective at this, both in her ability to detect situations in which collaboration appeared to be failing and in her ability to bring these situations to the attention of her classmates in a clear and non-offensive manner. Her comments in the following dialogue acknowledged the value of Robert's questions, but subtly reminded him that "We're all in this together." The discussion preceding this excerpt was centered around a piece of information Matthew had read about baking powder producing carbon dioxide gas. By this time, the students were aware that baking powder contains baking soda and is a base, and Carl and Keith had gathered and shared a convincing amount of evidence that carbon dioxide is the gas produced during the vinegar and baking soda reaction:

| | |
|---|---|
| Ms. S.: | So we have one more piece of evidence for who? |
| Robert: | Carl and Keith. |
| Samantha: | Basically for all of us, kind of. |

Andrea: What kind of liquid [needs to be mixed with the baking powder]? Just any liquid?

Ms. S.: Good question.

Matthew: It just said liquid.

Ms. S.: Okay. So what do you guys think? Are you in agreement with Carl and Keith's theory there?

Class: Yeah.

Ms. S.: Does anybody have anything to disagree with that?

Robert: I just don't.... They still haven't told us how the gas is made.

Ms. S.: Okay, so you agree that the particles break apart the way they do, but you want to know -

Robert: How they break apart and how the gas is made when they mix.

Samantha: You can work on that question, too. I think we're all pretty much stuck on that one.

Ms. S.: So is that a question that several of you have?

Class: Yeah.

Ms. S.: Is that maybe something we could talk about as a group, then? (Class Discussion, May 15)

Although the increasingly collaborative attitude toward meaning construction and debate appeared beneficial in many ways, the less-competitive approach to discussion likely influenced Carl's unwillingness to continue developing detailed explanations. It appears that "nobody knows" seemed to him a legitimate reason to terminate the theory-generating process, although it is possible that he was simply annoyed with the persistence of Robert's questioning. In any case, turning the question over to the entire class proved more productive than the interrogation-style dialogue that preceded

Samantha's suggestion of magnetic attraction as a mechanism for particle recombination.

In the end, Robert again presented his own ideas on the matter:

Carl: That's the gas from the baking soda and vinegar according to our theory, and we have some pretty strong evidence that points to that it is $CO_2$.

Ms. S.: Do you have a further question to that? Does that answer your question? Like, I'm not sure if that was -

Carl: He's asking how they break apart.

Ms. S.: So, you want to know why they come apart in the first place.

Robert: No. I'm asking what they do when they are apart. Like, when they link together making the gas, what is making them go together? What is making the C and the two O's go together to make $CO_2$?

Ms. S.: So, why would a C suddenly say, "Yo, join up with me, O"? Is that what you're wondering? Okay, this would be nice if we could get full involvement from everybody in this. This is something.... Like, it seems that everybody is stumped on it, so let's try and think of some solutions.

Matthew: Well, maybe it doesn't know what it is, and once it comes to it, it tries breaking off, but it can't.

Ms. S.: So, it tries because it wants to? It's alive? So it's going "Oo, I don't like being here. I want out"?

Carl: It's like that from the start. It's $NaHCO_3$. It's together from the beginning.

Ms. S.: So, why does it break?

Carl: I can't answer that.

Ms. S.: But can we try? Let's try and brainstorm some ideas here. What are some things that worked in the past for ideas? Do you remember from your idea sheet? Might you look back at that? What are some ways we get ideas? We're all stuck for an idea, so where can we get one?

Samantha: Maybe the vinegar is like a force. Maybe when the baking soda breaks off of the $NaHCO_3$.... Maybe it just sort of goes to the vinegar because the vinegar would be a force - almost like a magnet.

Ms. S.: So, there's like a magnetic attraction between the pieces?

Samantha: Yeah.

Ms. S.: Agree, disagree? Ideas?

Robert: I didn't hear it.

Ms. S.: Can you say it one more time, Samantha?

Samantha: Okay, um, when the $NaHCO_3$,.... When the baking soda breaks off.... When the little 3 breaks off and it makes it a 2, then in Carl's theory, it gets to the vinegar, because maybe the vinegar is like a force. Like magnets.

Robert: Why would they be attracted to it?

Carl: Opposites attract. A base and an acid. Opposites do attract.

Ms. S.: How are they opposite? What are you thinking?

Carl: Acids and bases.

Ms. S.: So, you're saying acids and bases, but what about them is opposite?

Robert: And how come the baking soda itself won't make carbon dioxide just by itself? How come it can't just use the oxygen?

Carl: I don't know.

Ms. S.: Well, it's a good question, though. Can you think.... Nobody's attacking each other. Try to remember that, okay? This is all of us working together to come to an answer. There's a question. Can we think on an answer? I don't think Robert has an answer for that question either, do you?

Robert: No.

Ms. S.: Does that mean we shouldn't ask it? Let's try and think of some answers. Can you say it again, Robert?

Robert: How come the C and two of the O's and the other one would go and link with something else? How come they won't make carbon dioxide?

Ms. S.: So, they're all stuck together in vinegar all the time. Why don't they just break apart all by themselves and make -

Carl: Both vinegar and baking soda can do it.

Ms. S.: They both have C's. They both have O's. Why don't they just break apart and make their own carbon dioxide? Why do they have to wait to be mixed? Is that what you're asking?

Robert: Mm hmm. And I've kind of got an idea that sodium is.... From what I've read, it's very active, and it can do a lot. It's a silvery white material, and it's very active when it's combined with oxygen. It's melted down, and then when it's exposed to air, well then it hardens. So, it reacts with many elements, and there isn't any elements different in vinegar than there is from baking soda except for the sodium. The sodium is the only thing that's different between the two, and one has more than the other. One has different stuff than the other.

Ms. S.: So, you're thinking the sodium is playing a part in all of this? (Class Discussion, May 15)

Although distrust of Robert's intentions is again evident in this discussion, his willingness to share his own ideas helped to minimize the antagonism that his questioning had elicited in previous discussions.

#### 4.2.3.2. Self-questioning.

In a further attempt to help the students move beyond arguing for the sake of arguing, I tried to encourage them to ask more questions of themselves rather than always waiting for others' questions. Typically, this was as simple as asking, "Do you have any questions for yourself?" instead of asking the questions myself. The students who participated in individual interviews were exposed to this technique earlier and more extensively than the other students, simply because of the extended one-on-one discussion time that the interviews provided. Often, asking the students to question their own ideas was sufficient to help them evaluate their ideas and required no further suggestion from me. When they had difficulty, I asked questions to help them take their investigations to a deeper level. In the following dialogue, Robert's and Samantha's reflections on their ability to engage in self-questioning illuminate both the general change in focus that was taking place in the classroom during this time period and individual challenges that these students faced in becoming more self-critical:

Ms. S.: Okay. So we're going to.... Last day you guys were all doing your own tests and coming up.... You're really getting good at coming up with your own questions. How do you feel about coming up with your own questions? How are you doing it?

Samantha: I'm getting better.

Ms. S.: You're getting better. And what are you doing to help you? What helps you come up with your own questions?

Samantha: I think of somebody else. You know how Robert always asks, "Why?" and "How?" and "What does this mean?" I read mine, and I say, "Robert's going to say this," and then, "Robert's going to say that, too."

Ms. S.: All right. And Robert? You were going to say something.

Robert: I go like that, too. And then I pretend that it's somebody else's rather than mine. Then it's easier to argue, because it's theirs and not mine.

Ms. S.: You don't like arguing with yourself, hey?

Robert: No.

Ms. S.: [laughing] Okay. Whatever it takes. Anybody else have things that are.... I'm noticing you're doing very well with that. What are you doing that's making you so good at this? Yeah?

Jennifer: I'm pretty much like Samantha's. Like, what will people ask me?

Frank: Mine's sort of like, "Well, what if this?" I keep asking myself, "What if that?"

Ms. S.: What ifs? You do a lot of what-if type questions?

Frank: Yeah. (Class Discussion, May 13)

Robert, Samantha, and Jennifer seem to have achieved at least a preliminary understanding of the following point from Sagan's "baloney detection kit":

> Try not to get overly attached to a hypothesis just because it's yours. It's only a way station in the pursuit of knowledge. Ask yourself why you like the idea. Compare it fairly with the alternatives. See if you can find reasons for rejecting it. If you don't, others will. (p. 210)

As the students shared their ideas later in the class period, conscious self-questioning was evident. In the following explanation, Samantha clearly identified several questions about which she was still wondering:

Samantha: I think that when they make the fizz and the gas, they separate into like, you have your baking soda and your vinegar and they break off into different groups, and I think how they break off is like.... I think they kind of eat at each other, and then they break apart. And I'm not really sure how they eat at each other yet. I'm still trying to figure that out. That was a question for myself. And I also have another question. Like, when they break apart into different groups, sort of, to make the fizz, I had the question of what if they get into the wrong group? Like, what if there's two baking sodas that end up together again? I haven't answered that question, either. And I was doing a test. I was testing baking soda and vinegar, and I kept adding 'till they wouldn't fizz anymore, and I was going to see if they made a new thing, and if there was baking soda left. I let it dry, and I wanted to see if there was still baking soda in it. To test that, I would add new vinegar, and if it fizzed, then it would be baking soda. But

> that didn't really work, 'cause I had way too much vinegar, so it didn't really dry out. (Class Discussion, May 13)

When the students identified their own questions, it seemed to take the sting out of being challenged by classmates.

In much the same manner as was identified in the previous section, there were times when students used the identification of unanswered questions as an excuse to avoid resolving difficult issues. In the following conversation, Carl identified questions that he was unable to answer, but used his acknowledgement of the inadequacies of his theory as an excuse for not resolving them:

> Carl: And, um, I'll start from the beginning. I think that when vinegar and baking soda meet, the vinegar takes one oxygen from the $NaHCO_3$, making the formula $NaHCO_2$. It's baking soda with one oxygen.
>
> Keith: How does it take one oxygen?
>
> Carl: That's one of the questions that I have for myself, and I can't answer that. I haven't figured it out yet. And then the $CO_2$ separates from the NaH, and that's why we get $CO_2$ gas. And the NaH combines with what's left of the $CH_3COOH$, making something new. So I don't know if anything happens or changes or gets missing from this one-from the vinegar - but I'm assuming that something does happen, and that's why I said "what's left of." And then the questions for myself was, "How does it take the oxygen?", and I still don't know. I'm trying to figure that out. And "What is the formula for the new substance, NaH combined with $CH_3COOH$?", and that I can't answer, either.
>
> Ms. S.: Not yet, anyway.
>
> Carl: Not yet. (Class Discussion, May 13)

When individual students invited the larger group to respond to their puzzles, collaboration was often effectively fostered. In the following example, Rachel's question is directed toward the class, and it generated results that she considered helpful:

Rachel: Like, how does it make the gas? Like, to have pressure on the balloon to make it go up, um, float.

Ms. S.: How does it make the gas? Is that what your question is?

Rachel: No, not how, but why does it make the balloon go up or get bigger?

Samantha: Maybe since it is making gas, and it goes up into the air, if you have a balloon over top, it would have to have somewhere to go.

Rachel: Because when you stick the balloon over top, nothing is getting in.

Ms. S.: In where?

Rachel: Like, okay, what happens sometimes is, uh, when you put baking soda.... Okay, you stick baking soda in something, and you put vinegar in, and then you quickly put a balloon over top. Nothing is getting in, and it still gets bigger.

Ms. S.: What do you mean nothing is getting in? Nothing is getting in where?

Rachel: Like, no air or anything is getting in to fill up the balloon.

Ms. S.: And so you're wondering where the gas to fill up the balloon comes from?

Rachel: Yeah.

Ms. S.: Any suggestions?

Rachel: To make a balloon bigger, we blow. We are putting something into it.

Jordan: Carbon dioxide.

Rachel: Yeah.

Samantha: Well if, when you put baking soda and vinegar in it, we're saying it makes this gas, right? It makes carbon dioxide, or we think it does. Then, um, if you put the balloon over top, and there's nothing in there but baking soda, vinegar, and the gas. Well, when the gas goes up into the air, then it has to have somewhere to go. Like, if you didn't have the balloon on top, it would just go out, but you have the balloon on top, so it goes into the balloon. So that's what is filling the balloon.

Jordan: I have a good point.

Ms. S.: Okay, just jump in whenever you think it fits.

Jordan: Okay. You know how we blow carbon dioxide into the balloon. Well, when we put the balloon over, it's exactly the same. Baking soda and vinegar are making carbon dioxide that goes into the balloon.

Robert: Supposedly it is making carbon dioxide.

Jordan: Yeah.

Carl: We have some proof, some strong proof.

Ms. S.: We have some evidence.

Carl: Evidence. Strong evidence.

Ms. S.: Strong evidence.

Jordan: So it would do the same thing as when we are blowing into the balloon.

Ms. S.: What do you think of that, Rachel?

Rachel: I think it's pretty good.

Ms. S.: Okay, does that help you at all?

Rachel: Yeah.

Ms. S.: So do you have any other questions or things that you want to pose to the class that would help you?

Rachel: No. I kind of think I have my answer now.

Ms. S.: Okay. Do you have any other questions that you were wondering about?

Rachel: Um, not really. (Class Discussion, May 15)

In the next situation, Andrea's self-identified question initiated a rather lengthy discussion regarding the nature of baking soda and baking powder and the role of pH levels in the vinegar and baking soda reaction:

Andrea: I was just checking all the pHs, and for vinegar it was pH 4. And that was an acid. And then I just did the school water just to see if it had anything in it, and it was pH 7. So was baking soda, but then when I put tape on it, it turned yellow. And then I tested it again, and I let it dry, and this time I don't know what pH it was, but it looked like this color [displaying a sample in her book]. It's probably about pH 6, maybe. And then I also had another question. Why does baking soda go up faster than baking powder? And I don't know the reason why yet, but I tested.... I'll just read you everything that I have. I tested this, and I put four of those spoons of baking soda and baking powder in each beaker. Then I put two spoons of baking soda and baking powder in one beaker, so that they were mixed. Then I put in vinegar up to the ten-mark in each beaker, and I noticed that the baking powder has bigger bubbles than when I mixed both at the beginning. When I mixed it at the beginning, it had small bubbles, but as it got bigger, the bubbles got big. So, when I first dumped the vinegar in, there were little bubbles, but then it came up medium, and the bubbles got bigger. I'm just trying to find out why it does that. (Class Discussion, May 15)

In a further attempt to help the students develop self-questioning strategies, I asked them to reflect upon sources of questions and ideas that commonly occurred during their discussions. How and why questions were immediately obvious to them, but the use of what-if questions evoked considerable debate. The following day, I showed the students a video of a previous discussion in an attempt to catalyze reflection on question-types. In the accompanying discussion, Robert struggled to explain a difficulty he perceived with what-if questions. He finally agreed that they could be useful, but only if they were "on topic." He indicated, though, that this qualification should apply to all questions, and clearly remained dissatisfied with his explanation. Unfortunately, he was unable to formulate one that more clearly designated what he wanted to say. At this point, I was unable to help him, as the difference between the productive and non-productive use of what-if questions was still unclear to me as well. This difficulty is the subject of an critical discussion in the analysis of implication-based evaluation in Section 4.3.3. As she reflected on questions evident in the video, Samantha identified, "If…, then what will happen?" as a question-type, and Andrea expanded this to include, "If not, then what will happen?". These are also important in developing the implications of a given idea, but neither I nor the students articulated a connection between what-if questions and predictive implications. Questions for clarification were also included in the list of question-types. Although the identified question-types were listed on the chalkboard and left for future reference and elaboration, there were no documented instances of the students using the list to help them pose questions for themselves. They continued to use questions that fit the category-types described, but there were no apparent conscious attempts to do so. The list seemed to serve little purpose in terms of providing starting points when the students were stuck for questions. My own lack of clarity regarding question types may have been part of the reason for this, however. Had I more effectively guided this discussion, valuable insights may have been gleaned from the students' comments, and these may have affected subsequent use of various types of questions. Further research is necessary to identify the importance of conscious understanding of questioning techniques.

#### 4.2.3.3. Other developments.

Throughout the unit, I encouraged the students to continue to add to the lists of things that helped and didn't help their discussions. Often, their contributions focused on classroom procedures that would better facilitate the type of discussion they had by now become accustomed to. For example, class discussions often led to the development of many new ideas for investigation, some of which required answers before the discussion could continue in a meaningful fashion. These tests were important, but they sometimes drew attention away from the point of the discussion. On one such occasion, I asked the class to suggest solutions to this difficulty:

> Ms. S.: Okay, we have a couple of demos here. I think Carl and Matthew.... Are you ready? Er, Frank, too? Okay, Jordan is. Can you guys.... Now you guys need to see this, too. Now how do you want to work this, because the people who are doing experiments are missing out on the discussion. Can we stop for a minute and work this out - how you think it would be best to organize this?
>
> Robert: Let's just all help on the experiments and then after they're finished -
>
> Jordan: I'm all set up.
>
> Jennifer: The one that's ready, let's do it, and then we can talk about it, and then the other can get ready.
>
> Ms. S.: Okay.
>
> Jordan: Okay. So, this tester [ohmmeter] is creating it's own energy -
>
> Ms. S.: Okay, sorry. Just a minute. Guys, we just agreed on something [Perhaps only I agreed. This discussion was somewhat rushed, and it is unclear whether others agreed with Jennifer's suggestion.]. Carl, do you not agree with that, or.... 'Cause, if you don't, you should say something. (Class Discussion, April 20)

Discussion of Jordan's test continued for some time, but when he went to get string to test a new idea suggested by a classmate, several students went back to their own experiments. The classroom atmosphere again became somewhat disjointed. At the end of the class, the students expressed concern with the effect that this had on their discussions:

Ms. S.: ...And if you have anything for our helped / didn't help list, could we talk about that for a moment?

Andrea: For the "didn't help" thing, there were too many people walking around doing experiments. Like, there were five doing one over there, and just one person.... 'Cause then no one's listening to you. So maybe just one experiment at a time.

Ms. S.: What do you guys think of that? Comments on what Andrea just said?

Robert: Well, I think sometimes we get everything done, and people have to be doing two things at once. Like, there has to be more people helping one person.

Ms. S.: So how should we handle that and still keep our discussion? What would be the best way to.... Like, Andrea, you said that you didn't feel like people were listening to you?

Samantha: Like, I was saying something to Frank, and he was off doing an experiment, so he didn't really hear a word I said about what he was doing.

Andrea: Maybe they could just test it on their own time, at recess or at home -

Robert: Then there's no point in testing it.

Andrea; You could come the next day and share your ideas.

Ms. S.: So, should we have a discussion day? And then when it's a discussion day, we'll write down the questions we need to test, and then when we're done discussion, we can go do all the tests? Would that be helpful?

Class: Yeah [nodding heads].

Ms. S.: What do you guys think of that?

Keith: I think maybe the people who are testing should pick the people who will go first, and then they listen to anybody's comments.... If someone's talking, they have to stop whatever they're doing and listen to the person who's talking.

Robert: That wouldn't work, 'cause.... We tried that. Like, Samantha was trying to get Frank's attention, and she repeated it a few times, and he was still working. (end of class) (Class Discussion, April 20)

Although no definite conclusions were reached on this matter, the students' concern with the issue and their attempts to seek solutions provide clear evidence of their ongoing efforts to improve the classroom context in which they generated and evaluated their ideas.

Clearly, significant changes occurred in the manner in which the students debated and discussed their ideas over the course of the five-month observation period. Their own reflections were highly influential in terms of manipulating the environment in which they continued to work. Throughout the time frame over which this evolution took place, the students were actively involved in generating ideas and in evaluating both their own and each other's ideas.

The diversity of student activity that resulted from the increased freedom granted in the chemistry unit provides a rich source of information regarding the manner in which different students approached the problem of explaining the vinegar and baking soda reaction. As a result, data from this unit is the primary source of information used in the development of the ideas pertaining to the approaches to inquiry documented in Section 4.3.1. Specific strategies by which the students were able to generate, evaluate, and communicate new ideas during both the electricity and chemistry units are explored in subsequent sections.

## 4.3. The Child-Scientist

*Charming child occupied with pleasure,*
*We jest at your fragile endeavors.*
*But between ourselves, what is more solid,*
*Our projects or your castles?*

\- Lepicié

Children require the ability to generate and evaluate their ideas both to develop scientific understandings and to effectively interact with their daily environments. Whether one's livelihood is science or otherwise, the ability to construct understanding of scientific ideas is critical to many aspects of life. To test their theories, children must investigate the implications of their ideas by means of process skills employed in the service of the meaningful context that the theories provide. However, when working in unfamiliar areas, articulating the theories that provide this context is a major stumbling block for many students. Some are able to generate and build upon ideas much more effectively than others. Identifying differences between the approaches used by students who experienced different levels of success in approaching such activity as well as identifying differences between students and scientists lies at the heart of this study. Delineating ways in which these differences manifested themselves in the context of the electricity and chemistry units through which the students worked is the focus of Section 4.3.

Analogy plays a pervasive role in both the generation and evaluation of ideas. All ideas and all arguments appear to be formed on the basis of what is already known, and evaluating the applicability of these analogies in new situations is critical to sound reasoning. This makes it very difficult to separate the knowledge-construction process into idea-generation and idea-evaluation components. Even the validation of an analogy may be done on the basis of another analogy, which Clement (1981) refers to as a bridging analogy. Theoretically, this process could extend ad infinitum. Essentially, effective idea-generation is dependent upon effective evaluation strategies, and effective evaluation is dependent upon generative processes associated with the use of analogy.

After many attempts to define and clarify and to classify and re-classify the main elements comprising the manner in which students construct scientific understandings, two factors have emerged as critical: (1) the ability to identify similarity, and (2) the ability to determine whether identified similarity is applicable in a new situation. Students naturally explore the effects of many stimuli in new and familiar contexts, and they naturally connect new ideas to those that they already have. This sort of unrestrained creativity partially defines the natural activity of all of the children observed. However, it appears that those students who are able to examine critically the applicability of the activities and analogies that they use are able to develop much deeper understandings than those who simply follow initial, intuitive responses to phenomena.

The ability to identify and evaluate similarity forms a unifying theme that underlies the criteria in each of the three main sections that comprise Section 4.3. In Section 4.3.1, different levels represent increasing ability to focus on a given question. This ability is presented as a product of growing awareness of the role of theory in the development of ideas. Section 4.3.2 focuses on analogical reasoning, and the ability to identify and critically evaluate the applicability of identified analogs is an important component of developing skill in this area. Finally, Section 4.3.3 focuses on the development of an understanding of the need to identify predictive implications as a means of testing and extending the applicability of a particular theory in a manner that helps to focus the wide variety of what-if questions that children seem naturally to generate. The main features of each of these categories are summarized in Table 1. This summary is followed by Figure 1, which provides a simplified view of this information that more clearly outlines the manner of progression between levels and more clearly portrays the relationship between elements of the three main frameworks. Table 2 summarizes the main features of student understandings of empirical processes and of the nature of communication that support the more general framework provided in Table 1. The nature of the relationship between the categories in Tables 1 and 2 is elaborated upon is Section 4.3.4.

The discussion of empirical processes in Section 4.3.4 is categorized according to traditional ways of describing school science that do not fit neatly within the framework described to this point. It includes a consideration of three factors: (a) fair-test procedures, (b) measurement and observation techniques, and (c) data analysis. Each of these plays a fundamental role in the evaluation of scientific knowledge, but focuses on a more specific element of reasoning that fits within the broader perspective provided by the framework presented in Sections 4.3.1 to 4.3.3.

Finally, the section on communication (Section 4.3.5) describes features of communication that appear to be fundamental to the generation and ongoing evaluation of the scientific ideas that took place during this study.

The criteria identified in this section were developed in the observational context of the specific type of classroom activity outlined in Section 4.2 and therefore assume that the activities in which the children engaged may be classified as genuine scientific activity. Such an assumption is necessary to judge the relative strengths and weaknesses of the students who were

**Table 1.** ***Developmental levels within each of the three major categories used to describe scientific reasoning.***

| | **Focus of Inquiry (FOI)** | **Analogical Reasoning (AR)** | **Implication-Based Evaluation (IE)** |
|---|---|---|---|
| **Level 1** | - Activity is based upon theories-in-action; a "guiding intellectual rule," and a "guiding motivational rule" (Duckworth, 1996, pp.18-19) are at the root of these theories.<br>- Activity is driven by perceptions of similarity, discrepancy, and novelty | - Analogy use is implicit. | - Relevant components (input) are identified and manipulated mentally to simulate observed phenomena (output).<br>- No conscious attempt is made to ensure consistency among parts of the theory, consistency with previous ideas or arguments, or between the theory and other observed instances in which the phenomena being explained interact (isolated-case reasoning). |
| **Level 2** | - Activity is focused upon external variables, and is commonly prefaced with, "What would happen if...?" It may involve:<br>  - familiar stimuli applied to novel materials or phenomena<br>  - novel stimuli applied to familiar materials or phenomena<br>- How- and why-questions are poorly understood. | - Implicit analogs are deliberately reified useful parts are identified / mapped.<br>- Understanding of source analog is confirmed.<br>- Likeness automatically indicates transferable explanatory structure: If *x* can do it, so can *y* (unless knowledge in a specific domain makes this implausible).<br>  - Negative components of analog relationships are either not noted or are explained away with, "It's just an analogy."<br>  - Proxy abstractions are used in place of clearly understood phenomena. | - A systematic attempt is made to explain situations in which the phenomena are known to interact. Previous arguments are considered at this level.<br>- The identification of similarity, discrepancy, and novelty during mental what-if explorations often leads to modification and elaboration of the theory being developed.<br>- Mental simulations are replayed to put ideas together in a more fluent manner.<br>- The understanding that it is almost always possible but not always plausible to explain away discrepancy via alterations to a theory may lead to the belief that rational explanation is not possible. |

|  |  |  |  |
|---|---|---|---|
| **Level 3** | - Activity is based upon internal variables; i.e. students at this level understand that a theoretical framework is necessary to drive focused observation.<br>- What-if questions are challenged on the basis of questions such as:<br>  - Why would that happen?<br>  - So what if it did?<br>At this point, however, they may not explicitly understand the importance of predictive implications to this process, which is the basis of the IE framework.<br>- The understanding that deeper levels of understanding may always be sought may lead to a sense of epistemological relativism. | - Likeness MAY indicate transferable explanatory structure: Why would *x* act like *y*? The transferability of explanatory structure is evaluated by means of one or more of the following:<br>  - conscious mapping of positive and negative components of analogs<br>  - bridging analogies<br>  - implications of the analog relationship (This strategy is only used explicitly at Level 3 IE.) | - Reflection on the nature of predictive implications in familiar situations leads to a systematic search for predictable and observable outcomes. This helps to resolve difficulties associated with ad hoc hypotheses identified at Level 2 IE. |
| **Level 4** | - Understanding of the subjective nature of knowledge leads to systematic attempts to disconfirm theories. | - Deliberate attempts are made to identify implicit mental models that may be unconsciously affecting thoughts regarding phenomena being explained. | - Alternative implications are sought. |

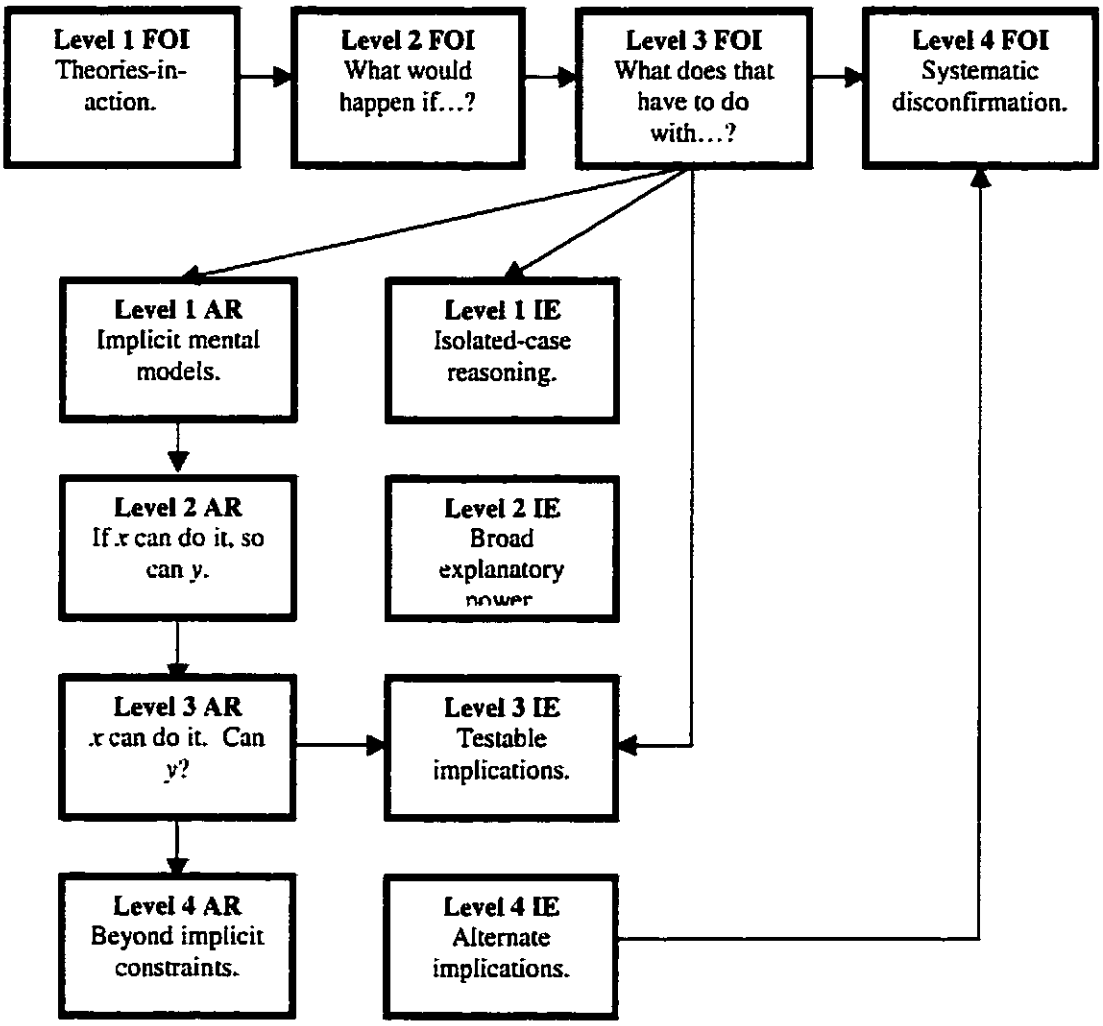


***Figure 1.*** **How students generate and evaluate scientific ideas: A developmental progression.**

**Table 2:** ***Developmental levels within the categories pertaining to empirical procedures and communication skills.***

| | Designing a Fair Test | Measurement and Observation | Data Analysis | Communication |
|---|---|---|---|---|
| **Level 1** | - Assumed causation based on a single observation | - observations based on unaided senses with no recognition of sensory fallibility | - conclusions based on a single case | - alternate views perceived as wrong (egocentrism) |
| **Level 2** | - domain-specific fair test procedures | - observations based standardized measures (as needed) | - general impressions from the data are used to support original theory<br>- counter-evidence is typically overlooked | - sincere consideration of alternate views |
| **Level 3** | - abstracted understanding of rational fair-test procedures | - measurement techniques designed to emphasize differences among observation samples<br>- amount of variation that could be due to observer or instrument error taken into account | - evidence is carefully analyzed for both supporting evidence and counter-evidence<br>- techniques for sorting data may be employed to highlight patterns and anomalies | - attempts are made to use others' theories to think about phenomena in question |
| **Level 4** | - explicit understanding of the need for a control | - observations sought to counter the effects of seeing what is expected | - alternative interpretations of data are carefully considered | - recognition of interpretation bias |

involved. However, the validity of such activity is strengthened by the students' demonstrations of characteristics that are identified in the literature as typical of scientists.

Each of the categories described to this point has been divided into four sub-sections describing levels of performance that appear to form a developmental progression. The fourth-level categories are based primarily on evidence from studies of experts, and the first-level categories are based primarily on studies of young children. For the most part, it is the second and third-level categories that have been defined by the nature of the thought and activity exemplified by the students who took part in this study. As a result, these typically form the bulk of the discussion within each main section. The first and fourth-level categories have been included primarily to demonstrate the manner in which extension in either direction of the evidence gathered here form a plausible developmental progression.

There is evidence that progression between levels involves the development of metacognitive understandings that allow the students to transcend ways of thinking typical of previous levels. Old ways of thinking remain important, but metacognitive understandings of these ways of thinking allow them to be used in more rational ways. In other words, although thinking processes common among students at lower levels may still be acceptable and even necessary at higher levels, metacognitive awareness of the role of various thought processes significantly impacts the manner in which ideas are used at higher levels. Progress between levels is catalyzed by a process of reflective abstraction, in which reflection on thinking deepens understanding of thought processes in a manner that facilitates the development of more advanced and more deliberate ways of thinking. Reifying modes of thinking employed subconsciously at lower levels in familiar contexts allows them to be consciously and thereby systematically employed at higher levels, even in unfamiliar contexts. In developing the levels for each category, a general progression from implicit to explicit use of scientific thinking strategies is evident. It is interesting that these ways of thinking appear to develop in a manner similar to that of scientific knowledge.

During the initial stages of identifying levels within each of the major themes, a difficulty arose in attempting to categorize students' thinking in that many of the categories appeared dependent on the context of the investigation; i.e. they appeared to be domain specific. According to Vosniadou (1989), "what is developed is *not* the analogical mechanism itself but the conceptual system upon which this system operates" (p. 414). This concurs with current interpretations of Piagetian-style development (Carey, 1985; Duckworth, 1996). If this is true, however, what is it that allows some students to develop the conceptual systems that so obviously better facilitate the generation and evaluation of scientific ideas in unfamiliar contexts? It is this question that the developed categories attempt to address. An important difference between students who consistently demonstrate criteria typical of the higher levels and those who only do so when working in familiar domains is the conscious and systematic use of strategies that are used implicitly when operating within familiar domains. Metacognitive understandings appear to develop in a manner similar to other content understandings. Once such an understanding has been identified and reduced to abstraction within a familiar domain, the generalized understanding thereby created may drive a search for constituent parts even in domains where the content itself does not make the need for certain strategies obvious. If this is the case, the futility of attempting to teach the thinking processes outside of a reflective context in which the students construct their own understandings about thinking should be readily apparent.

Of course, this only pushes the question regarding why some students progress through these levels more quickly than others to a deeper level. Why do some students form the systematic metacognitive understandings that allow rational thinking skills to be employed in new domains? Growth between levels may occur in a predictable progression, but appears to be influenced by the nature of the activities in which the students take part and appears to involve the degree of content-based and metacognitive reflection in which they engage as they do so. If Gardner (1983) is correct, the ability to engage in self-reflection may involve a specific intelligence of its own. The driving and developmental factors influencing self-reflection are beyond the scope of this paper, but developing an understanding of their role will need to be addressed at some point.

It is undeniable that scientists have a much broader and more integrated knowledge base than Grade Five and Six students do, regardless of the levels at which the students interact with ideas and construct new knowledge. They also have a much larger repertoire of specific mathematical and scientific procedural tools to employ as they evaluate their theories. The basic argument put forth here is that the strategies that students who participated in this study used to generate and evaluate their ideas are both a fundamental part of true scientific thought and important steps in a developmental progression toward the habits of thought used by actual scientists. I will argue that children develop these ways of thinking by participating in and reflecting upon activities that engage them in the process of constructing meaning.

### 4.3.1. Focus of inquiry (FOI): A developmental approach to epistemology.

> *The principle of science, the definition, almost, is the following:* The test of all knowledge is experiment. *Experiment is the* sole judge *of scientific "truth." But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it gives us hints. But also needed is* imagination *to create from these hints the great generalizations – to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess.*
>
> (Feynman, 1995, p. 2)

"Focus of Inquiry" (FOI) describes the nature of the ideas and questions that provided the directional impetus for children's investigation of the broader questions for investigation that framed this study; i.e. "How does a battery work" and "Why do vinegar and baking soda react the way that they do?" There appear to be close connections between students' approaches to investigation and their epistemological understandings of the nature of science. The role of theory is critical to each, and the development of this understanding is one of the main features distinguishing different levels within the FOI framework. In Chapter Two, the role of students' ability to generate new ideas was suggested as a critical factor (and, in its absence, a critical stumbling block) affecting their ability to explain scientific phenomena. This remains an important area of study and is examined further in Section 4.3.2. However, the difficulty seems more deeply rooted than this in that some students do not seem to have a generalized understanding of what is meant by questions like "How…?" or "Why…?" Without this understanding, they are unable to formulate theories to guide their investigations of phenomena. Being able to understand such questions is pre-requisite to theory-development, and therefore directly influences levels of FOI. Consequently, students' beliefs about causation are also included within this framework.

Briefly, the four levels may be summarized as follows:

1. Level 1: Theories are limited to implicit expectations, which drive the recognition of similarity, discrepancy, and novelty and which appear to drive investigation at this level. Students do not articulate what it is they are trying to find out.
2. Level 2: Students do not articulate explicit theories, but do specify what it is they are trying to find out or accomplish. They often do not understand the intent of questions such as "How…?" and "Why…?" Investigations are typically based on finding out, "What would happen if…?" or "How can I make it…?" as students deliberately investigate the effects of familiar stimuli in novel situations or the effects of novel stimuli in familiar situations. Controlled testing is common, but these tests are typically based on external variables with no hypothesized causal role in the phenomena being explained.
3. Level 3: Students understand what "How…?" and "Why…?" mean and use this understanding to develop theories. They recognize the importance of a guiding theory and connect their ideas to this theory. Controlled investigations are based on internal variables with a hypothesized causal role in the phenomena being explained. They recognize the need to rationalize what-would-happen-if (WWHI) questions by explaining their potential relevance to the question being investigated. Although this often involves the use of questions such as, "Why would that happen?" (WWTH) or "So what if it did?" (SWIID), students at this level do not explicitly recognize the importance of predictive implications to this process. The development of this understanding is dealt with in Section 4.3.3.3 as part of the IE framework.

4. Level 4: Students recognize the theory-dependence of observation and the consequent subjectivity of the knowledge developed as specific theories are investigated. Because objective knowledge is viewed as impossible, disconfirmation becomes a critical strategy when evaluating theory. Full development of Level 4 FOI was not observed in students taking part in this study, and it seems likely that understandings specific to both the AR and IE frameworks developed in Sections 4.3.2 and 4.3.3 may be critical to the development of this understanding.

Considerable evidence for the existence of the four identified FOI levels is drawn from an analysis of the data in the chemistry unit, as the students had much more freedom to influence the direction of their investigations within the classroom context in which this unit took place. They worked individually except when they chose to work temporarily with a partner whose investigations they deemed relevant to their own, and the majority of the activities were selected by individual students. Because sustained attention to a series of related investigations is an important criterion for Level 3 FOI, a context such as this is clearly essential for the demonstration of this approach. Transcripts of individual interviews and classroom discussions from the electricity unit did require sustained attention for the development of a theoretical model of a battery, but the nature of attention thus sustained was more heavily constrained by the trajectory of classroom discussion than it was during the chemistry unit.

All of the students observed during this study worked at either Level 2 or Level 3 FOI, and limited evidence of the beginnings of transition to Level 4 was observed in some cases. Further evidence of Level 4 activity is drawn from the literature pertaining to expert strategies for generating and evaluating ideas. The existence of Level 1 FOI is based primarily on evidence in the literature that pertains to young children's approaches to science (Henriques, 1990), although examples of this type of activity seem to be scattered among higher-level activities.

I have included a discussion of some of the initial difficulties and ambiguities in the development of the FOI levels in Appendix H.1. This should help to clarify the form in which they now appear. I have also attempted to explain the process of transition between these categories by relating them to work by Moshman and Lukin (1989). Further support for the categories and the manner of transition between them is drawn from connections between the FOI levels and Carey et al.'s (1989) and Carey and Smith's (1995) work pertaining to children's beliefs about science. Their ideas are discussed in greater depth in Appendix H.2.

#### 4.3.1.1. Level 1: Theories-in-action.

At Level 1 FOI, students do not or cannot articulate the intent of their activities: "When one asks him, 'What are you doing?' he often replies 'Nothing' or 'I don't know,' but goes on with the activity quite seriously" (Henriques, 1990, p. 159). Activity at this level is likely guided by implicit expectations that influence perceptions of novelty, discrepancy, and similarity. These expectations will be referred to as "theories-in-action," which have been defined as the "implicit ideas or changing modes of representation" (Karmiloff-Smith & Inhelder, 1975, p. 196) underlying children's actions.

None of the students in the current study had any difficulty articulating what they were doing as they engaged in various activities. This may be due in part to their age, the amount of direction (albeit limited) provided by the focus questions, and / or the students' prior experience with the materials with which they were working. However, the implicit expectations that appear to drive activity at Level 1 may play a role in defining interest in events that often catch the students' attention as they apply various stimuli in the context of more focused activity.

If this is the case, elements of Level 1 FOI may be evidenced in the subjects of this study. At Level 1, the child applies stimuli known to have an effect in familiar contexts without identified expectation or intent and proceeds according to the generation of effects identified as similar, discrepant, or novel. These may be briefly defined as follows:

1. Similarity: Students notice something new that they are able to explain in a manner similar to another situation with which they are familiar; e.g. Jordan noticed that to register a current, the probes of an ohmmeter had to be placed in the same tray of vinegar, "...just like a battery! It has to be on the same one or it doesn't work!" (Field Notes, April 2). Frank's observation of a bulb evoked a similar response: "Yeah. I just noticed something now, though. There's those little toaster things there [He is looking at the filament in a bulb when he makes this statement and then proceeds to light the bulb]. Oh, cool! Yeah, it's like it just lights up right there" (Battery Interview, March 16).
2. Discrepancy: Students notice something new that contradicts expectations that are based on another situation with which they are familiar; e.g. Jennifer commented, "It fizzes when you put in new baking, or vinegar,

but not when you put in new baking soda.... That's weird" [stirring mixture] (Class Discussion, April 20).

3. Novelty: Students notice something that they did not expect to happen, but for which they are unable to articulate prior expectations as justification for their surprise; i.e. something new catches their attention. This is a subset of the discrepancy category in that the surprise is likely incited by the violation of implicit expectations; e.g. Rachel commented, "What I thought was really neat was there was our last petri dish. It had little bubbles with little holes underneath. I don't know which one it was, but it was kind of neat" (Class Discussion, May 22).

All of these involve the interaction of new events with prior knowledge. In these cases, the explicit articulation of expectations is unnecessary to generate interest or facilitate observation. Attention to events such as these likely drives Level I activity.

Microscope observations were a particularly rich source of examples of students taking marked interest in observations with no apparent connection to an investigative context and in which novelty seemed to be the motivating factor:

Ms. S.: Make sure you all get a look in the microscope, okay? Did you get to see yet, Rebecca?

Class: [looking at microscope] That is so cool! Let me look!

Frank: Ms. S., Ms. S., you should come and take a look at this!

Ms. S.: No Jordan? Okay, there was a couple here. I think, Jordan, what they're looking at is, uh, baking soda and vinegar.

Jordan: Can I see?

Ms. S.: Is this still baking soda and vinegar?

Class: Yeah.

Ms. S.: You might want to make a little diagram of what you saw so that you can remember it.

Matthew: It looks like Jell-O!

Ms. S.: If you're waiting and you've already seen, why don't you go make a quick drawing of what you looked at.

Frank: I gotta take one more look.

Ms. S.: Okay. I don't know if the lamp works, but you can try it, Carl.

Matthew: That is like a wicked....

...

Robert: Hurry guys, you can see it fizzing!

Jennifer: Let me see, let me see!

Frank: You can see the alcohol is just barely fizzing.

Class: Neat!

Matthew: Looks like little salt particles.

Robert: I know.

Matthew: That is wicked!

...

Carl: It looks like a rectangular prism or something.

Ms. S.: Does it?

Carl: If you could get it on its end that would be better.

Andrea: Whoa!

...

Carl: Ms. S., I have it on the highest power possible. [The students come over to look.]

Ms. S.: Is everybody getting a diagram of what baking soda looks like under the microscope?

Class: Yes. Yeah. Oh.

Ms. S.: It's on high power now over here.

Keith: It's like totally clear!

...

Frank: Oh, Ms. S.! Come and look at this!

Jordan: Let me see! [Many students gather around to watch Frank.]

Frank: Crystals! White crystals!

Keith: That's a humungous crystal.

Matthew: It's wicked!

...

Matthew: [looking into microscope] Wow! That is the best crystal, yet! (Class Discussion, April 20)

Discrepancy also captivated the students' attention. Samantha's initial fascination with salt crystals was rooted in their variance from the types of crystals to which she had become accustomed during previous tests of a similar nature:

Samantha: Yeah. It tastes like salt and vinegar. And it used to be all gooped together, and when it reacted, maybe under a microscope it bubbled just a little bit. You know how peroxide bubbles when you put it on a cut? Maybe it did that just a little bit. But not enough to see with your two eyes or whatever. And when it dried, the salt dried in bigger crystals. Some dried in really big crystals, and some dried like really small crystals, sort of like in its own group. (Class Discussion, May 15)

By Level 2 FOI, interest-catching events may prompt articulated attempts to simulate or extend understanding by the application of various stimuli. By Level 3 FOI, they are either noted with interest while the students maintain focus on an identified task, or comprise a conscious and temporary diversion from that task. This is not intended to suggest that unexpected observations are always irrelevant or that important investigations cannot be precipitated in this manner. Many serendipitous discoveries are dependent upon the pursuit of an interesting observation (R. Roberts, 1989). By Level 3 FOI, however, pursuing interesting but divergent leads involves a conscious choice to shift the focus of inquiry. The apparent contradiction between the inherent value of following such leads and that of maintaining a clear focus on a specified topic is discussed further in Appendix H.3.

Duckworth (1996) identified two guiding rules for intellectual activity in young children:

> Infants begin to act in intelligent ways from the day of their birth, that is, they make connections, seek consistencies, and modify their actions in terms of their situation. One might say that they are armed initially with nothing more than their reflexes; a guiding *motivational* rule that might be stated like this, "If I can do it, I will"; and a guiding *intellectual* rule that might be stated, "All else being equal, things will turn out the same." (pp. 18-19)

The "guiding intellectual rule" could account for children's tendency to engage in exploratory activities that do not appear explicitly connected to a guiding theoretical framework, and the "guiding motivational rule" could encompass unarticulated motives for acting on materials in familiar ways. Together, these may drive both inquiry and technologically based activity.

If observation is truly rooted in theory (T. Kuhn, 1970), it seems likely that students who were unable to articulate a purpose for their investigations (Henriques, 1990) had implicit expectations that guided their activity. These expectations may have been sensory in nature, which would also help to account for the difficulty they had in articulating them.

Carey (1995, 1996) and Carey and Spelke (1994) have suggested that implicit "intuitive theories" (Carey, 1996, p. 189) guide the thinking of very young children, and explore the possibility that these theories may be rooted in "innate cognitive modules" (p. 187). So far, they have identified three such modules: One pertains to the physical world, one to people, and one to number. If they are correct, Duckworth's (1996) "guiding intellectual rule" and "guiding motivational rule" (pp. 18-19) should be sufficient to prompt student investigation. According to Carey and Spelke (1994), the tendency for infants to "look longer at displays that they perceive to be novel" (p. 172) is well documented, lending further support to this idea.

The main difference between Level 1 and Level 2 FOI is the students' conscious awareness of what is driving activity. To reiterate, the inability to articulate expectations or questions that drive activity need not suggest the absence of such expectations. There may exist physical expectations that have no verbally abstracted counterpart. However, the ability to articulate questions and / or expectations provides a means of focusing activity in a way that allows more explicit development of theory. This is the first level of reflective abstraction as it pertains to this framework.

According to Carey et al.'s (1989) Level 1 epistemology:

> ...the students make no explicit distinction between ideas and activities for generating ideas, especially arguments. The nature of 'it' remains

> unspecified or ambiguous; 'it' could be an idea, a thing, an invention, or an experiment. The motivation for an activity is the achievement of the activity itself, rather than the construction of tested ideas. The goal of science is to discover facts and answers about the world and to invent things. (p. 520)

These beliefs about the nature of science are consistent with the types of activity which typify Level 1 FOI in that they exemplify the lack of a perceived need to specify in advance what it is that the student hopes to find out. 'To discover facts and answers about the world' and 'to invent things' are both consistent with activity characteristic of Level 1 FOI.

At Level 2 FOI, students may or may not spontaneously articulate expectations regarding what will happen as they attempt to generate effects, as understanding why a particular phenomenon occurs is not the primary focus of activity at this level. That they are able to do so upon request suggests a metacognitive barrier rooted in the lack of a perceived need to articulate expectations rather than a procedural or cognitive barrier regarding the ability to do so. All of the students observed during this study were able to articulate the intent of their activities, but many had difficulty focusing their activities on the guiding question provided for the unit. This difficulty partially defines Level 2 FOI.

#### 4.3.1.2. Level 2: Exploration and effect-seeking: "Test it."

> *A great deal of scientific discovery has come, and for children or adults can come, from a curiosity that focuses on rather everyday phenomena, but that does so with a refinement of discrimination that our normal working routines do not involve. This curiosity, this impulse to explore, to uncover phenomena previously overlooked or hidden, and to enjoy them, is minimized or overlooked in many discussions. It is overlooked because of a second phase of experience, which we more often call curiosity. This phase often follows the first but is dominated by how or why questions rather than the direct enjoyment of fresh experience. Yet without the first phase the second is unmotivated; without the second the process cannot be extended.*
>
> (Hawkins, 1990, p. 100)

Level 2 FOI is characterized by effect-seeking. Activity is primarily aimed at producing either novel or preconceived outcomes, and investigations can typically be prefaced with, "How can I…?" or "What would happen if…?" Consequently, it may be separated into two categories: (a) goal-directed activity and (b) effect-seeking activity. Any investigation involving external variables is classified at Level 2 FOI. Students engaged in activity at this level typically attempt to find out what happens when familiar stimuli are applied in new situations or when new stimuli are applied in familiar situations. These stimuli are external variables in that the students are not interested in determining their roles within broader explanations and therefore do not have benchmarks against which to judge their relevance. Anything that seems a likely stimulus for an effect of some sort qualifies as relevant to a student at Level 2 FOI. Attempts at explanation are primarily descriptive at this level, and attempts to elicit responses to questions pertaining to how or why a particular phenomenon may have occurred are typically not understood. This may help to explain why students at this level tend to focus on the WWHI investigations that typify Level 2 FOI. Without considering how or why a phenomenon occurs, developing a theory is impossible. It appears that helping students to understand what is being requested when how or why questions are posed may be an important step in helping them progress toward the theory-based experimentation that becomes evident at Level 3 FOI.

Carey et al. (1989) described a Level 2 understanding of the nature of science as follows:

> Students make a clear distinction between ideas and experiments. The motivation for experimentation is to test an idea to see if it is right. There is an understanding that the results of an experiment may lead to the abandonment or revision of an idea. However, an idea is still a guess; it is

> not a prediction derivable from a general theory. (Indeed, students may not yet have the general idea of a theory.) There is no appreciation that the revised idea must now encompass all the data, the new and the old, and that if a prediction is falsified, the theory may have to be revised. (as summarized by Carey & Smith, 1995, p. 53)

This is consistent with the tendency of students classified as Level 2 FOI to test a variety of unconnected ideas to find out "What would happen if...?" for no theoretically motivated reason. Typically, students at Level 2 FOI have ideas about what will happen, which is what motivates their activity in the first place. Because these ideas are not grounded in a theoretical framework pertaining to the focus question, however, they often remain unconnected after they are tested. This may partially explain the tendency toward isolated-case reasoning that students at this level tend to display. This is discussed in greater detail in Section 4.3.3.1. Carey et al.'s (1989) description of the "guiding ideas and questions" of students at this level is particularly illustrative of Level 2 FOI: "In level 2 answers, exploration is guided by a particular idea, question, object or phenomenon, e.g., a scientist 'walks through a forest and finds something new and tries to find out more about it'" (p. 524). In this study, "it" seemed to refer primarily to particular phenomena rather than to testable explanations of those phenomena. For example, when questioned regarding how they might find out more about these phenomena, students at Level 2 FOI commonly respond with statements such as, "Test it" or "Do tests on it." In this context, "it" does not seem to refer to a theory or an idea at all. The students apply different stimuli to observe the changes that they may effect in doing so.

There were occasions when students designed well-articulated theories with identified and rationalized implications that had no bearing on the guiding question. Although they identified these implications without determining their relevance of their ideas to the broader explanatory framework, these cases displayed theory-based experimentation in which the students could have related the results to a guiding theory. Typically, however, they did not relate them back to ostensibly guiding theories, which indicates that the generation of effects likely remained the driving force behind their activity. The identification of implications may have been a secondary interest or a response to teacher or peer questioning that consistently asked, "How will that help you understand...?" It is also possible that apparent inconsistencies such as these may be partly due to domain-specific knowledge that allows a rationalized focus in one context but not another. The appearance of isolated cases of apparent Level 3 FOI is not cause for classifying a student at that level, as it does not demonstrate systematic and conscious application of the understandings associated with this level. This issue is discussed in greater detail in Appendix H.4.

Some of the activities currently classified at Level 2 FOI may also be classified at various levels of a yet-to-be-developed technological framework. The reason that technologically oriented activity only appears in Levels 1 and 2 in the FOI framework is that by Level 3, the students are explicitly focused on inquiry-based activity and focus their activities accordingly. The likelihood that such activity could provide a strong foundation for technologically oriented goals should not be overlooked and is discussed further in Appendix H.5.

#### 4.3.1.2.1. Beliefs about causation.

Difficulty generating ideas and / or ways to test them appears to form a significant barrier to Level 3 FOI. As will be seen in other applicable sections, this has important implications for the manner in which students deal with analog relationships, poorly understood or proxy abstractions, and descriptions of interactions between features identified as salient. Students at Level 2 FOI cannot move past descriptive explanations, because they do not yet understand what is meant by successive levels of why. In some cases, "attributing the cause of … physical phenomena to procedures" (Wong, 1996, p. 501) stifled questioning of this nature, because the students honestly believed they had developed complete explanations and therefore did not see a need to keep asking, "Why…?" or "How…?" This is very evident in much of Jennifer's work. Her initial explanation of the vinegar and baking soda reaction reads as follows:

> What is the gas and how did it get created? Viniger creates the gas. What happens when you mix Baking Soda and Viniger? I think when you mix baking soda and viniger some sort of strange gas gets created and rises into the air. You have a bottle put some baking soda in the bottom, have a balloon ready. Put some viniger in and put the balloon over, then it blows up. Sometimes it looks like theres no baking soda even though theres lots. When the viniger drys up the baking soda shows up. (Journal, April 20)

Her explanation almost sounds like a step-by-step list of instructions describing how to replicate the investigation. Her initial attempt at describing a battery model was very similar. She explained that when the wires connect to the terminals of the battery, an alleged divider in the middle of the battery breaks and allows acid from each side to mix. According to her theory, this creates energy, which is able to get out through tiny holes located at each terminal. She also suggested that a live battery is filled with acid and a dead battery with base. After being barraged by her classmates with questions regarding how the divider would break, Jennifer simply explained that the divider breaks when the wires connect. This was immediately met with another chorus of hows and whys. She went on to explain that both the minus side and the plus side push against the divider's middle and cause it to become "feeble" and crack. Then the minus side stops pushing and the plus side pushes harder, causing the divider to break and the acids to mix and create energy. Further hows, whys, and attempts at explanation followed.

Jennifer's difficulty understanding the need to go beyond mere description is also very evident in her responses to Robert's persistent questioning regarding how the gas in the vinegar and baking soda is formed during the reaction. Robert's Level 3 FOI understanding is evident in his understanding of the need to probe for deeper explanation. As Jennifer attempted to explain her ideas, he repeatedly asked how and why the gas is made. Her responses indicate a persistent belief that "mixing" is sufficient explanation:

Robert: What is this strange gas?

Jennifer: I knew you were going to ask that! First the vinegar and baking soda creates the gas when it mixes together.

Robert: What is the gas?

Jennifer: Um.... Well the gas.... You know, like, when things collide. People hit each other, right? Their fist beats their face or whatever. That hurts, right? And then they usually cry or whatever, so when the vinegar hits the baking soda, it will -

Robert: Start to cry?

Jennifer: Sort of, yeah. It cries, then. Then you create the bubbles, 'cause you're boiling mad, and then the blood stinks. Okay?

...

Andrea: Jennifer, what did you say about what the strange gas is?

Jennifer: Like, for the answer? The force of the baking soda and vinegar creates the gas.

Robert: But still. What is the gas? The force of the baking soda and vinegar is the gas, but how is that making the gas?

Jennifer: Okay. Here's your little baking soda bunch [drawing on blackboard]. Then here comes the vinegar. And it gets mad because it's hitting it, like, charging into it. They collide, right? So, each one is getting mad at the other, right? The vinegar has to hit the baking soda harder than the baking soda hits the vinegar.

Robert: Why?

Jennifer: Okay, forget that. One has to hit the other harder than the other one.

Robert: Why?

Jennifer: I'm getting to it. You know the vinegar has to drop in, and you already have the baking soda down here, and it's all nice and flaky, right? Well, this has to drop in and, it can come in super hard, right, and hit the baking soda, which will make it mad.

Robert: Why?

Jennifer: Well, I think that there were little things of baking soda, right? And then you put the vinegar in, right? And it bubbles. Those are air bubbles trying to get out, right? Yeah. So, then you know when we had the baking soda and the vinegar and the candle, right? We put the baking soda in, then you light the candle and put it in, and then you take the eyedropper full of vinegar and put it in, and the candle would slowly run out, right? Because it didn't have any oxygen. We would slowly die because we didn't have any oxygen.

Robert: How did we get the gas to put the candle out?

Jennifer: Fire needs oxygen to burn, right? We need oxygen to live just like a candle, right? So, if there's gas all around, and you have this big of a beaker, right, and you put lots and lots of baking soda in it and put the candle in and light it, and then you put the vinegar in it, it's going to die. Well, not die. It's going to burn out, because it didn't have as much oxygen as it needs.

Robert: But where did you get the gas to put it out? Not why is it going out. Where is the gas to put it out coming from?

Chorus: From the vinegar and baking soda mixing.

Robert: How does the vinegar and baking soda mix to make a gas? How does that make a gas?

...

Robert: When they mix, what does that do? That doesn't help me. They mix to make a gas. Oh well, what does mixing it do to make a gas? When my sister fights me, I don't make gas.

Samantha: But those are chemicals. You and your sister aren't chemicals.

Jennifer: Beans. You eat beans, right? And beans usually make you have gas.

Robert: But when I fight, the gas doesn't come out.

Jennifer: Okay, well you eat the beans, right? And something in your stomach doesn't really like the beans, and it makes your stomach upset.

Robert: So vinegar eats beans?

Jennifer: Just forget the vinegar and baking soda right now. We're talking about beans and stomachs. Maybe the stomach doesn't like beans. The stomach likes the beans as much as the vinegar likes the baking soda. They hate each other. So, the beans make the stomach upset, so then you get gas, and sometimes you vomit, right? And then you have to find some way...

Robert: How do you get gas? That's my question. Why do you get gas? They mix. They're upset about each other. How does that make gas?

Frank: Has anyone seen *Dante's Peak*? When that lava goes into the water, and it's more like acid, isn't it? And then when it kills something, it will steam, right? So, it'll make gas.

Robert: That's because it's so hot, Frank.

Jennifer: Then how does the grandmother's legs get eaten? Steam doesn't eat your legs. Acid does.

Frank: The heat doesn't eat your leg, does it?

Robert: Uh, I think that if I put a candle under my leg, it'll eat it.

Jennifer: It'll just burn it.

Class: It won't eat it. It'll burn it.

Robert: Well, it's still going away.

Carl: There's not going to be any blood, though.

Jennifer: And vinegar is some sort of acid, right? Shh! Let me talk! You've got your air bubbles, right? These are the air bubbles. They're trying to get out of there, 'cause it doesn't have any room.

Jordan: What are the air bubbles?

Robert: In vinegar, there is air.

Ms. S.: So are the bubbles the gas that's being made, or are they regular air?

Jennifer: They're regular air that's being trapped in there.

Ms. S.: So, like air bubbles trapped between the pieces of baking soda you mean?

Jennifer: Yeah.

Ms. S.: Okay. And that's different from the gas that gets made? Is that what you're saying?

Jennifer: Yeah.

Frank: Back to that idea with the acid. Let's say that acid is the vinegar, right? Except that it's not quite as strong. And this is sodium carbonate. And let's say that you put it in with it, right? When two acids mix.... Here's the $CO_2$ and here's the acid. You take the acid and you pour it into the baking soda and they're trying to....

Like on the volcano, if you touch it, it will eat metal, right? The acid would, so let's say this is trying to kill it all, right? But since it's not a strong enough acid, it doesn't fizz as much.

Robert: That doesn't help me. I want to know how you get gas.

...

Jennifer: Okay. Now we're trying to know what the gas is, right? Now everybody knows what vinegar smells like, right? It smells pretty gross. And everything has it's own smell. You don't even have to smell it, but it has it's own smell. So, you can't really smell the baking soda smell but it has a smell.

Jordan: Well, how do you know what its smell is?

Jennifer: So, the strange gas is when you mix the two together. So, you can't really smell the baking soda smell, but you can smell the vinegar smell. So, when you mix the two together, well, you don't smell as much as vinegar, but it probably smells more dry, and you can't tell that. But even though it's sticking together like mud, it still smells dry like flour. Smell it. Okay, Jordan. What do you think about it?

...

Robert: So, is that all of your explanation?

Jennifer: Play-dough usually smells like salt. Is there salt in there? Okay, does anybody have anything to add?

Robert: That still doesn't tell us how the gas is made.

Jennifer: Well, it makes the gas when it mixes.

Robert: That doesn't tell me how it makes the gas.

Jennifer: If you smell vinegar by itself and baking soda by itself, you will usually smell the vinegar stronger. Gas is when these two mix.

...

Jennifer: The gas is made.... Keith, what are you doing? The gas is made.... You have your baking soda, right? You have your baking soda down in your little cup thing or whatever you're mixing it in. It smells just fine, right? But then you pour the vinegar in. Then the gas is created cause it mixes up. Like when you're making cookies, everything smells different when it's done, right? Okay, so when it's all mixed together, it smells different. So, the gas is made when it's all mixed together. Get it?

Robert: But how is the gas made?

Ms. S.: Would you like to hear what Robert has to say?

Jennifer: Okay.

...

Robert: Here's our little beaker thing here, and I've got my baking soda in it. It smells. It doesn't matter about the smell. I don't care about the smell. Then you drop in the vinegar. Then it mixes up, and all you're saying is smell. Like, I want to know how this gas is made - how the gas comes up.

Jennifer: It mixes.

Robert: See, it's mixing here, but that doesn't tell me how the gas is made.

Jennifer: Yeah it does. It's mixing.

Ms. S.: But if you mix salt water and sand, would it make gas?

Jennifer: You go to the beach, right. And there's lots and lots of waves, and sometimes....

Robert: That's foam from hitting the rocks.

Jennifer: It's mixing.

Keith: That's air and the water making air bubbles.

Samantha: If you mix vinegar and baking soda and you put it on your finger and you pick it up, there's vinegar and baking soda on your finger.

Jennifer: And it fizzes still.

Samantha: Yes, but if you take sand and salt water in your hand, it's not fizzy.

Matthew: Because it isn't an acid.

Samantha: Exactly.

Robert: Let's say this is your acid and this is your baking soda. When you mix them together, you're just saying that they mix together. I don't see how the gas is made.

Jennifer: When it mixes together, see it's mixing, mixing, mixing. When it's mixing, out comes the gas. 'Cause there's no room for the gas in there when it's mixing.

Robert: Where does the gas come from in the first place?

Jennifer: When it's mixing. It's a gas. You can't really smell it when you're doing it.

Robert: Where does the gas come from?

Carl: Robert, instead of asking her stupid questions, why don't you just give her an idea.

Ms. S.: Is this a good time for an idea?

Class: This is the best time. (Class Discussion, April 22)

Clearly, Jennifer believed that she had provided a clear causal explanation, and, being unable to see the point of Robert's line of questioning, became quite irritated with him. As was shown in Section 4.2, other members of the class shared her irritation, some because they shared her confusion regarding the point of his questioning, and others because they resented what they perceived as ulterior motives driven by Robert's well-known competitive nature. Just before Robert was given the chance to share his idea, Samantha shared a comment that demonstrates the dawning of an understanding of Robert's persistent questions:

Samantha: I just have a definition of "how" for everybody who thinks that me and Robert are just pestering you guys. Okay, how. If you take vinegar and baking soda, air bubbles rise up because they're trying to get through, so they push them to the side. How do you make an omelet? You don't mix it together and there's your omelet. How? You put the eggs in and then you mix it, and then you put the cheese in, and you flip the omelet over, and then you can stick mushrooms in it or whatever, and then you put it on the plate.

Carl: It has to have heat, too.

Samantha: Yeah. Do you see what I mean? You can't just put it together and there's your gas. Maybe the reason we can see tiny, tiny pebbles is because the sand and the water is rubbing together and then little pieces fall off. That is "how." That's not just mixing.

However, Samantha's later judgement of Robert's explanation as a "perfect definition of 'how'" makes clear that she had not yet generalized her understanding of the question in a manner that fully recognized potential levels of why:

Frank: Okay, Robert, show your idea.

Robert: Okay, here's my picture. In my acid, it's kind of like liquid air. Let's just call it liquid air. And my baking soda. So this is my solid air.

Matthew: What do you mean by "solid air"?

Robert: It's not air but it's, like, solid. And when these mix, a gas is made. This gas causes pressure, causing a cork on a bottle to blow off or a balloon to blow up. The bubbles are made by gas escaping through the vinegar and baking soda. Gas is made when the vinegar and baking soda combine.

Jennifer: That's exactly the same thing I'm saying only different words.

Robert: I keep saying, "Gas is made," 'cause I couldn't think of anything.

Jordan: Robert, that is exactly what she was trying to say.

Robert: I'm not finished. Those are my first things that I had. Gas is made because a new molecule is made. It stopped because the air has made bubbles filling in the space of the gas. Gas is made when the acid and baking soda are pressed together making a new material like air. The air on the baking soda and the air on the vinegar are a different shape because one material is a solid and one is a liquid. When they mix, the air is - made it react to each other, causing movement.

Samantha: That is "how". That is a perfect definition of "how." He said they combined together and they make something new. And he explained what "new" was.

Jennifer: That is exactly the same thing that I said just in more scientific words.

Samantha: You were talking about smell. He's talking about making new things.

Ms. S.: But didn't she say something about new things? Isn't the gas a new thing?

Robert: And I've said what made the new thing.

Ms. S.: Okay. So, Robert, you explained that it compressed and that's what made it?

Robert: It compressed and then it moves. When it moves, it makes the gas.

Ms. S.: Anyone have a question for that?

Frank's and Matthew's understandings of the point of asking, "Why…?" (at least in this context) became evident as they prompted Robert to elaborate. Near the end of the class, Frank pushed the discussion onto a new plane:

Frank: See, the vinegar's still here. You said that they're moving, right? Does it look like it right now that they're moving?

Robert: No. I said that the air inside of it was moving, not the actual thing. This air inside of it, not this thing.

Frank: How did the air get inside of it then?

Samantha: It's atoms, Frank. Everything has atoms in it.

Robert: This atom here gets along with this atom here, then they don't cause a reaction. And maybe a stronger vinegar has more of these little electrons on. Everything has something in it. Maybe it's like blood.

Frank: I got a question to ask you. Why do atoms affect the way the gas happens?

At this point, Jennifer was able to help further the discussion:

Jennifer: First, I'll need you to go to page eleven.

Andrea: I found this gas.... The electron is named after the Greek word for amber.

...

Jennifer: Okay, now you have your vinegar atom, right, and it looks like that. And it's a positive one. And the baking soda atom looks like that, right, and it's a positive. Now on that page, you can tell that a positive and a positive repel like that, and a positive and a negative will come together like that. But those two are positives, so that's what's making the gas. They hit each other so hard that they go back up, and that's what's making the gas.

Ms. S.: So, it's bits of what going up, then?

Jennifer: It's bits of both of them, because -

Ms. S.: So the gas is bits of vinegar and bits of baking soda flying out of the thing?

Jennifer: Yeah.

Robert: If you put certain amount of baking soda and a certain amount of vinegar in, and let's say you weighed one and then you weighed the other, and then you dumped the vinegar in, and then you let it fizz, and then you put it on the scale again, would it weigh the same amount?

Jennifer: Say that again.

Robert: Let's say you put.... I'll draw it. It's easier. Okay, you've got this here, and this is vinegar. You've got baking soda. The same amount. So you weigh this one, and let's say it weighs three grams. You weigh this one, and let's say it weighs four grams. Then you put this into there and you let it bubble. And then this mixture should weigh seven grams all together, and you put it on the scale. Will it still weigh seven grams? 'Cause you're saying that you're losing stuff, but are you?

Jennifer: Okay, since you've got more of the vinegar -

Ms. S.: Is it possible to test this?

Robert: Yes.

Ms. S.: Could we test if it loses mass after it reacts?

Jennifer: Okay, like, they're probably going to weigh maybe a gram difference, so maybe it'll be five grams there instead of six grams, because when these two mix, little bits of it are heating up, so maybe one gram of stuff is shooting out.

Robert: Can we test this now?

At this point, Robert was quite convinced that testing the mass would disprove Jennifer's idea and was eager to try it out.

A five-day lapse occurred between this discussion and the next, and the implicated missing mass was not immediately dealt with at the next session. Despite the time lapse, Frank was eager to re-open the discussion about positive and negative atoms:

Frank: Are we going to continue our argue thing from last day? 'Cause I've got something to argue about with Jennifer.

Ms. S.: Okay, so where were we at last day? Jennifer, do you want to summarize where you got to?

Jennifer: Okay. But I was getting to how the gas is made...how the two makes the gas. The question was, uh, "How does the mixing of the two make the gas?" or whatever. And I had some of the plus atoms and negative stuff and stuff like that.

Ms. S.: Okay. Can you say that again more slowly? This was new. I don't know if everybody heard this last day. Did you catch that everyone? This was the beginnings of her idea of how they make gas.

Jennifer: Yeah. 'Cause I had a vinegar atom and baking soda atom, and they're both positive. It seems the same sort of atoms doesn't attract. They repel. But different atoms, they attract.

Frank: Okay, you said there was a plus and plus atom. What would happen if an atom got in there that was negative? What if it was negative?

Jennifer: Then it probably, like, if you had a plus, plus, negative, or if you had a plus and a negative?

Frank: Then it would attract it.

Jennifer: Yeah.

Frank: And that's what makes the gas, or what? (Class Discussion, April 27)

At this point, an important barrier to understanding the meaning of why questions appears to have been broken. That Jennifer still had such a barrier after overcoming a similar one in the development of her battery suggests that her understanding of this concept may still have been domain-specific. Perhaps by the end of the chemistry discussion this understanding had become more generalized, but this was not observed. Samantha's comment seems to speak for many: "When Robert asks why, it takes a while to find out what he actually means" (Field Notes, April 29).

Ensuing discussion continued throughout the eighty-minute class period and covered a variety of topics, ranging from why "positive atoms from the air" do not enter into the reaction to the consideration of a variety of implications of a rearranging-particle theory suggested by Samantha. The discussion included a consideration of the nature of attraction between particles, the necessity of ending up with the same particles that were present in the initial substances (a rudimentary version of the law of conservation of matter), the difference between a chemical reaction and dissolving, and how to separate solutes from solvents by means of evaporation. All of these concepts were discussed in the context of the broader question and therefore had immediate relevance to the students' arguments. Further discussion of the importance of the contextualized development of understanding is included in Section 5.1.2.

Several of the students culminated the unit with persistent questions that emphasized their understanding of deeper levels of causation, at least in this context. Carl, Keith, Samantha, and Robert all articulated questions regarding the nature of the forces driving the separation and recombination of particles that constituted the most fully developed explanation of the vinegar and baking soda reaction that the students had articulated by that point. A magnet analog was quite popular, but both Robert and Carl recognized serious limitations to the relationship between the two, and Keith wanted to know what would make the magnet-like force work.

Recognition of the need to develop deeper levels of explanation also occurred in more specific contexts pertaining to the transfer of explanatory structure between analogs (particularly with respect to animist analogs), the rationalization of variables as salient, and the need to unpack proxy abstractions. These issues are further addressed in the specific contexts to which they apply.

#### 4.3.1.2.2. Investigating external variables.

Student investigations at Level 2 FOI are not directed at investigating preconceived ideas, but are deliberate attempts to find out how materials behave when exposed to various stimuli known by the student to have an effect in other situations. This is the basis of the WWHI preface that is commonly used to articulate investigative intent at this level. These investigations may be classified into two broad categories:

1. the application of familiar stimuli to novel phenomena (e.g. heating reactants, quantitative variation of various components)
2. the application of novel stimuli to familiar phenomena (e.g. testing vinegar with familiar household chemicals such as salt)

One of Rebecca's comments provides an apt portrayal of the mindset that drives the first type of activity:

> Rebecca: I have an idea. You know how last year we were growing bean plants, and I was growing one in the closet and one on the shelf and one underneath that light? Well, the one in the closet turned white, and the one under there, it was like green, and the other one was really green under the lights, so maybe we could see what would happen. Maybe it [baking soda] would change color or something [if it were put in the closet]. (Class Discussion, May 22)

Here, she clearly articulated her view that a stimulus known to work in one situation could act as a causal agent in another very different situation. A similar comment by Rachel provided a rationale for heating vinegar prior to mixing it with baking soda:

> Rachel: Uh, I just thought of another idea. A couple of years ago, we did warm water, and we stuck food coloring in it, and the food coloring spread more quickly than cold water. So, I was thinking of boiling vinegar and sticking baking soda in it and seeing what happens. (Class Discussion, May 22)

Neither Rebecca nor Rachel has explained how knowing whether baking soda turns green or that something happens to the reaction when it is heated might contribute to understanding how the reaction occurs. Apparently, they just wanted to find out if a familiar effect would follow a familiar stimulus in a new situation. This is the essence of Level 2 FOI. This relates to the AR criteria discussed in Section 4.3.2 in that the application of proposed stimuli is based upon analogy for which transferability of explanatory structure may be confirmed by the generation of the anticipated effect.

The application of novel stimuli to familiar phenomena was also a common source of WWHI activity. In Appendix H.1, statements prefaced with, "It has something to do with..." are identified as "vague hypotheses," which are able to frame experimental activity. However, sometimes statements such as these appear to be the foundation of theory-based activity but are investigated in ways that stray from their apparent focus on the guiding question. As Andrea was trying to explain the vinegar and baking soda reaction, she noted that it behaved like a battery. She suggested that in both cases something was being used up, but that the battery used different materials than the baking soda and vinegar reaction. She then suggested that the difference must have something to do with the baking soda, and set out to test baking soda with a wide variety of other household substances. However, she had no apparent guiding theory to help her select these substances. Her work was guided by a vague general theory ("It has something to do with baking soda"), but her failure to identify what it might have to do with baking soda (either before or after her tests) limits the classification of her investigation to Level 2 FOI. Essentially, she identified a new stimulus and tested its effects on a variety of other familiar substances. At best, she could have found out that baking soda indeed reacts with other substances. Even if it did, however, she would not have improved her understanding of the vinegar and baking soda reaction.

By comparison, one of Clement's (1989b) experts attempted to explain the operation of a double-width spring by first noting that it behaved like a lever: The wider the spring, the greater the leverage and therefore the greater the bending of the spring. Like Andrea, he also noticed a difference between potential analogs: There is no cumulative bending in the spring. Also like Andrea, he identified a vague hypothesis to guide his investigation. This was evident when he decided that the cumulative bending must have something to do with the circularity of the spring, as this was the main difference he could see between the straight lever and the spring. He then mentally substituted other factors for the feature proposed as salient. In his case, different coil-shapes were used as substitutes, and he was able to observe imagined differences effected by the various coils. In considering a square coil in this manner, it became clear to him that a torsion effect was acting on the spring in a manner that would not occur in a simple lever. If Andrea had identified a specific feature of baking soda that may have been responsible for the difference between the battery and the vinegar and baking soda reaction, her selection of alternate substances may have been guided by this criterion and may have helped her to identify what it is about baking soda that causes it to behave in the manner that it does.

Rebecca identified pH as something that was likely important to vinegar and baking soda reaction, but she did not specify a reason for her choice and did not set about testing the effect of pH in a systematic manner. In the following dialogue, she shared her findings about what baking soda is made of. Jennifer's comments demonstrate the beginnings of a rationale for the salience of pH in her identification of tomato juice as something that stings, but the connection between tomato juice and the reactants and between stinging and the reaction is never clearly developed. Matthew's suggestion that "If you put anything in a cut, it's going to sting more than it does" prompted the introduction of other substances for comparison to tomato juice. This demonstrates an attempt to determine if the property of stinging is unique to tomato juice, but the connection of this to the vinegar and baking soda reaction had still not been made. Although Andrea's reasoning regarding the tomato juice may be challenged, she refocused the discussion on the vinegar and baking soda, thereby demonstrating thought consistent with Level 3 FOI. As has already been shown, however, she did not consistently maintain such a focus, and therefore cannot be said to have developed a generalized understanding of the defining criteria for Level 3 FOI:

Rebecca: This is the pH paper. Look what it turned [showing the class the paper].

Carl: What is that?

Rebecca: This is the pH paper

Matthew: What number is it?

Rebecca: Number seven...

Andrea: Well, you said before that you thought there was something in baking soda. What was that?

Rebecca: Well, an acid.

Matthew: A powder acid.

Andrea: Um.... Well, what about, like, tomato juice and vinegar? Like, it couldn't be powder acid or whatever, because what would be in the tomato? 'Cause it fizzes. It doesn't fizz lots, but you can hear when you put your ear to it.

Jennifer: And when you have a cut, and you put tomato juice in it, it stings. Whatever that has to do with it.

Matthew: If you put anything in a cut, it's going to sting more than it does.

Ms. S.: Is that true? Does anything sting in a cut?

Class: No. No. Mostly. Sometimes. Water and milk don't.

Matthew: Hot water does.

Jennifer: Kim snipped her finger like this, and she put it under water and she said it stung, but anything hurts to her. Even when you go like this [touching her neighbor and saying, "Waaaah!"]. (Class Discussion, April 20)

In the following excerpt from Frank's individual chemistry interview, he identified finding out "more on hydrogen" as the next question he wanted to focus his investigations upon. However, the tests he suggested were aimed at determining how hydrogen behaves in a variety of circumstances, none of which was necessarily connected to the phenomenon he was trying to explain:

Frank: Uh.... I'm trying to find out some more on hydrogen

Ms. S.: Like, what about hydrogen would you like to find out?

Frank: I want to see what happens to it. So I can get some hydrogen and put it in baking soda

Ms. S.: And why would you do that?

Frank: I don't know. Just to see what happens, and maybe - and maybe even try to evac - try to evaporate the hydrogen - hydrogen. I don't know. (Chemistry Interview, June 5)

Clearly, there are multiple ways by which students identify sources of WWHI activity to drive Level 2 FOI investigations. By Level 3, students do not uncritically apply stimuli just because they think they might have some sort of effect on the phenomena being tested. At this level, they develop theories as a means of rationalizing the relevance of chosen variables and conduct investigations to determine whether their theories are right.

### 4.3.1.3. Level 3: Sustained focus on increasing explanatory depth.

> *It turns out that today we have approximately thirty particles, and it is very difficult to understand the relationships of all these particles, and what nature wants them for, or what the connections are from one to another. We do not today understand these various particles as different aspects of the same thing, and the fact that we have so many unconnected particles is a representation of the fact that we have so much unconnected information without a good theory. After the great success of quantum electrodynamics, there is a certain amount of knowledge of nuclear physics which is rough knowledge, sort of half experience and half theory, assuming a type of force between protons and neutrons and seeing what will happen, but not really understanding where the force comes in.*
>
> (Feynman, 1995, p. 39)

By Level 3 FOI, students consistently frame their activities within an integrating theoretical framework that asks, "How...?" and "Why...?" They are explicitly aware of the inefficiency of unfocused investigation aimed at producing effects and maintain a consistent focus on a series of related investigations. As students challenge the focus of each other's investigations, this often takes the form of questions such as, "What will that tell us about...?" Arguments based on WWHI formulations are explicitly challenged at this level in a manner that involves questions that essentially ask, "Why would that happen?" (WWTH) or "So what if it did?" (SWIID). Questions such as these may lead to the identification of predictive implications, but students at Level 3 FOI do not have an explicit understanding of the importance of identifying the implications of their ideas. This occurs at the next level of reflective abstraction. Rather than discussing this at Level 4 FOI, however, the deliberate search for predictive implications is discussed in relation to Level 3 IE (Section 4.3.3.3). Understanding the need for predictive implications appears to be driven by the reflective contexts of both frameworks.

Challenges based on WWTH or SWIID formulations are also important considerations in the evaluation of why selected analogs should apply in unfamiliar situations, but the fact that none of the students made deliberate use of to evaluate analogies outside the domain of animism suggests that metacognitive understandings specific to the nature of analogy are likely involved. Therefore, analogy is presented as a separate category in Section 4.3.2.

Students at Level 3 FOI may focus on identifying salient features and isolating them to determine their role in the phenomena that they are attempting to explain (i.e. via a vague hypothesis) or may formulate detailed descriptions of the inter-relationships between identified variables (i.e. via a specific hypothesis). Regardless of which approach(es) they use, students operating at Level 3 FOI consistently relate new evidence to the theoretical frameworks that motivated the search for that information.

Coming to terms with the relativistic hopelessness that may accompany the realization that there is always room for a deeper explanation or always another way to explain something is a prerequisite for transition to Level 4 FOI. This likely occurs as the result of reflection on both FOI and IE criteria. For the students observed during this study, relativistic views seem to be based more on the difficulties they often experience in developing testable implications that would (in their minds) prove their ideas than they are on true comprehension of the Level 4 FOI understanding that ideas are theory-dependent and therefore cannot be proven.

According to Carey et al.'s (1989) description of a Level 3 understanding of the nature of science:

> Students make a clear distinction between ideas and experiments, and they understand that the motivation for experiments is verification for exploration. Added to this is an appreciation of the relation between the results of an experiment (especially unexpected ones) and the theory leading to the prediction. (as summarized in Carey & Smith, 1995, p. 53)

This is consistent with observations of student activity in which investigation is both driven by and related back to a guiding theoretical framework.

Students at Level 3 FOI attempt to disconfirm their theories only when they perceive them to be faulty in some way and are typically better at providing arguments against others' theories than they are at providing arguments against their own. Often, although evidence is gathered that is likely to support the theories that they have developed, no deliberate attempts are made to refute them. Furthermore, students sometimes consider alternative explanations, but they have not yet developed the habit of systematic disconfirmation that Tweney (1991) attributed to Faraday:

> Out of this view, Faraday drew a kind of humility that was of great usefulness to his scientific work. Alert to the possibility of self-deception,

> he was consciously aware of the danger of confirmation bias and of the need to avoid it by deliberate attempts to disconfirm. (p. 7)

Significant understandings that must be achieved for a student to be classified at Level 3 FOI include: (a) a theoretical framework is necessary to drive focused observation and (b) deeper levels of understanding may always be sought.

#### 4.3.1.3.1. "But you could keep asking, "Why?" forever!"

> *The same thrill, the same awe and mystery, comes again and again when we look at any question deeply enough. With more knowledge comes a deeper, more wonderful mystery, luring one on to penetrate deeper still. Never concerned that the answer may prove disappointing, with pleasure and confidence we turn over each new stone to find unimagined strangeness leading on to more wonderful questions and mysteries – certainly a grand adventure!*
>
> (Feynman, 1988, p. 243)

As students at Level 3 FOI continue to pursue deeper levels of explanation, they typically come to realize that, "Why…?" may be used ad infinitum to elicit explanation at levels of increasing depth. At times, this seems to spawn intrigue, but it may also provoke the belief that seeking deeper understandings is a somewhat futile endeavor. The interest that several of the students showed in the possibility of the unlimited divisibility of matter is a good example of their fascination with infinite whys:

> Samantha: It seems that, like, you can take something, like, you can take.... If you take sugar, for example. You take sugar, and then it has its ingredients. And then it has, like, glucose in it, and then you can get ingredients out of that, and then that has hydrogen in it, and then you can get ingredients out of hydrogen, and then you take those ingredients, and you can get more ingredients. It seems like it keeps going and going.

Ms. S.: And actually that's a big question in science. Wanna hear one of those history stories like Thomas Edison?

Class: Yeah!

Ms. S.: Okay. It's not actually something they tried, but a long time ago, okay, you know how we talk about atoms? Like hydrogen is an atom and oxygen is an atom.

Class: Yeah.

Ms. S.: And we put atoms together to make stuff. Like, Samantha's talking about ingredients. You take those ingredients and you take all your atoms, and you put them together to make something, like molecules. Right? Well, the ancient Greeks thought.... They had a big argument. Can you keep breaking it down? Like, when you get to an atom, can you break an atom in half and have ingredients from the atom? Can you have the ingredients for the ingredients for the atom? Like, where do you end? Can you just keep breaking them down forever? And some people said, "No, once you get to an atom, that's as small as you can get." Some people said, "No, you can keep chopping and chopping and chopping, and you'll get smaller and smaller and smaller."

Carl: You did that with the Junior Highs. You said, um, you have super-vision, and you have super sharp knives. Okay, you take a gold brick, cut it in half, and finally you get down to the molecules. Can you cut that in half, and will it still be gold?

Ms. S.: What do you think?

Carl: No.

Ms. S.: So if you get down to the smallest molecule, can you break it in half?

Carl: No. Well yes you can, but it won't be the same material as you started off with.

Ms. S.: Okay. So what if you take glucose and break it apart, do you still have glucose?

Class: No.

Ms. S.: But do you still have something?

Class: Yes.

Ms. S.: Okay. What if you take -

Keith: You don't have one thing, you have two things.

Ms. S.: Okay. What if you took hydrogen and broke it apart? Do you still have hydrogen?

Carl: There's no hydrogen anymore, because you broke it apart.

Keith: No, that's splitting an atom.

Ms. S.: Then what happens?

Carl: Then you'd explode. You'd turn white and fall to ashes.

Ms. S.: [laughing] Okay, but scientists are now finding, like, we used to think.... We knew nothing smaller than an atom. But now scientists talk about things called protons and neutrons and electrons which make up atoms. And then there's even smaller particles that.

Carl: Has anybody ever seen an atom?

Class: No.

Carl: Then how do we know that it even exists?

Ms. S.: Good question. Any ideas?

Class: [everybody talking at once]

Carl: No, have they ever seen one singular atom all by itself?

Keith: You could never.

Carl: Then how do you know it exists? How do people know it exists? It could be just a myth that caught on and kept going.

Andrea: Why do they call them atoms? Why don't they call them Andreas?

Class: [laughing]

Ms. S.: [laughing] Good question, though. It sounds funny, but it's true. Why do we call them atoms?

Robert: What keeps our desks together, then?

Carl: Screws, welding.

Ms. S.: That's a good question, though. What keeps them all together?

Robert: If the screws came together, what would keep the screws together?

Carl: Nothing.

Robert: Yeah. You need something to hold it together. So like, atoms would explain what holds things together.

Class: [all talking at once]

Ms. S.: How so, Keith?

Keith: Atoms. We started it in batteries.

Ms. S.: Okay. You know what guys? You've asked some really huge questions, and you just might find that they have a lot to do with baking soda and vinegar and maybe even with batteries. It's amazing how these things start to connect. (Class Discussion, May 25)

At this point, the students' ideas remained full of inaccurate conceptions. More important, though, is that they were asking questions that allowed such in-depth consideration of these ideas in the first place.

Sometimes probing for deeper levels of why led to explanations and arguments that some students considered less than adequate. Robert identified concern with what he termed "off-the-head" arguments. This is discussed further in

Section 4.3.3.2.2. For Carl, the belief that he was unable to prove his ideas became a source of frustration that he was unable to transcend independently. His struggles to come to terms with this frustration are highlighted in Section 4.3.3.2.3.

#### 4.3.1.3.2. Focused experimentation based on internal variables.

By Level 3 FOI, students are explicitly aware of the need for articulating a theory prior to conducting investigations. They now recognize the lack of focus inherent in investigations focused on external variables and deliberately center their activity around articulated ideas. These ideas may be either vague or specific hypotheses, but the results of investigations based on these ideas must contribute to understanding of the focus question. WWHI questions assume a different role in this context: Mental explorations based on WWHI formulations continue, but the relevance of both stimulus and implication must be established before they may serve as legitimate springboards for argument or investigation. Because students at this level may not have an explicit understanding of the need to develop implications of their theories as a means of testing them, they sometimes experience frustration at this point.

In Chapter Two, I suggest that children's apparent difficulties understanding the "point of experimentation" (Carey et al., 1989, p. 516) are likely the product of their being asked to explore questions that are not their own. Children focus very effectively on experiments when the contexts of those experiments are familiar to them. However, a more domain-general appreciation of this concept may also be possible. I propose this as a metacognitive understanding that needs to be learned through direct challenge of unfocused activity. Throughout the collection of dialogue that follows, evidence is provided that some students are able to provide this sort of challenge for their peers. This is particularly evident in Robert's arguments regarding attention to stimuli with lack of or yet-to-be-identified relevance.

Both Andrea and Robert challenged Matthew on the point of testing different types of water with vinegar and baking soda. Samantha's response indicates that her judgement of Matthew's activity as relevant was based on her understanding of a more general guiding theory regarding a definition of chemistry as "when you mix two things to make something":

Andrea: This is sort of the same question as Robert's, but why did you test that? How does it relate to -

Matthew: Well, I was going to find out what the difference was between jug water and normal tap water, and so I mixed it with the same. Just this is jug water, and this is tap water.

Robert: But did you find out about vinegar and baking soda?

Samantha: Yeah. He wanted to see if there was a difference, like to see when you mix vinegar and baking soda.... If he was going to mix it with water, water had an effect on the gas, and if you tested it and you wanted the gas to go up, and all of a sudden you found all this gunk in your baking soda and vinegar, then you would.... Like, if you tested it with tap water and you didn't know anything else, then you'd be saying, "Oh look, the vinegar made this, and the baking soda made this, and the gas turns purple" when really it's just the goop from your tap water.

Robert: Why would you test it with water in the first place?

Samantha: To see if it has an effect on the gas.

Robert: And why would you want to figure out what water has to do with vinegar and baking soda? You haven't even figured out what vinegar and baking soda do.

Ms. S.: So, if you were growing crystals just with water, but we weren't using water, is that what you're saying? If you were using vinegar and baking soda, water shouldn't have been something that affected the tests, because we weren't using water. Is that what you're saying?

Robert: Yes. And there's water in vinegar already anyway.

Ms. S.: So why add water, you're saying.

Samantha: Well, chemistry is when you mix two things to make something, and when you mix baking soda and vinegar, I think it makes two things. Like zinc sulfide or something like that, when you mix zinc and sulfide in water, something does that. Anyways, if you mix baking soda and vinegar, like, according to all our stuff, it makes fizz and gas. And if you add water, then maybe it adds something. It does something to the gas, though, 'cause so far we've found out that it's $CO_2$, but if you add something different, then.... Well, Keith and Carl are testing the gas, and so we know what the gas is, and we pretty much know the crystals that it makes. And we're studying the crystals now under the microscopes, and we know all that stuff.

Robert: Yeah, but we don't know what happens to make that stuff. There's no point in doing all this after-stuff if we don't know what happens in the first place.

Ms. S.: So do you mean why do these particles come apart and go back together anyways?

Robert: Yes.

Matthew: Well, we could probably get clues from after.

Robert: Yes, but we're doing too many things of after. We're adding stuff after.

Ms. S.: So you're saying we should also ask, "What does sand do to it? What does copper do to it? Why don't we add a little pond water? Maybe some bugs, too." Is that what you're saying?

Robert: Yeah. That's basically what we're starting to do. (Class Discussion, May 22)

This discussion clearly highlights the difference between focused and non-focused activity, and it emphasizes the metacognitive differences regarding this matter that are inherent in the ideas of different students. Matthew saw no problem with seeking clues in random activity, whereas Robert expressed a strong belief in the need to consider the relevance of activity before engaging in it.

Robert also challenged the point of Samantha and Jennifer's crystal-growing activity. The two girls had spent a considerable amount of time investigating the types of crystals that form after vinegar and baking soda react and are left out to dry. Samantha's initial interest in crystals did not emerge from a clearly focused goal aimed at developing a better understanding of the vinegar and baking soda reaction, and later uncertainty regarding the point of this activity may have been due to a somewhat unfocused motivation for doing the investigation in the first place. This difficulty was likely exacerbated by the imposition of my suggestions regarding a useful crystal-growing activity:

Samantha: Okay. We found this tree here, and it says "Magic Grow Tree" [reading from book]: "Amazingly, when the paper is set up like a tree and the solution is placed on its base, the tree will flower and blossom over the following twenty-four hours."

Ms. S.: And does it tell what it's made of?

Samantha: Um, no it doesn't. But it's, like, with the crystals, though.

Ms. S.: Okay.

Samantha: Like we could see if we could -

Ms. S.: So we want to see what kinds of crystals we can make?

Samantha: We should see, maybe, if we mix different things.... We could see what kinds of crystals it makes. And then maybe we can, like.... Then maybe we can.... Like, it says that you put paper.... Maybe we can do that, and then pour the solution over top if we find something that makes crystals like that.

Ms. S.: So you mean mix a whole bunch of stuff and make our own crystals?

Samantha: Yeah.

Ms. S.: Is everybody here hearing this? There's a lot of people wandering about looking different ways. Okay, Samantha, can you say again what it is that you thought you might do to identify the crystals.

Samantha: Um, like the crystals.... Instead of just buying this kit or anything, it says, um, when the paper is set up like a tree, and the solution is placed on its base or whatever, then, um, maybe I was thinking if, uh, we think up crystals that are kind of the same. Like, if we use different solutions from the cart, and we can make up crystals that are sort of drawn really neat and look like that. Maybe we can try and make our own.

Ms. S.: Okay, but is our goal to make really neat crystals, or is our goal to find out what's in the petri dish? (Class Discussion, May 15)

As the discussion continued, my own interest in comparing crystals of vinegar and baking soda with crystals of the products of the reaction between them likely influenced my belief that Jennifer was suggesting something similar. Based on her later inability to articulate the point of the crystal tests and on the manner in which she and Samantha conducted the test, it seems likely that she had something else in mind:

Jennifer: Well, while we're trying to make the crystals like this, we can write down what it is. Like, we can put it in.

Ms. S.: And then how would that help us, Jennifer?

Jennifer: Well, if they look like this, then it was like, I don't know, whatever you wrote down for it. Then it could tell you what's in here [showing petri dish].

Ms. S.: So it would help us find out what's in the petri dish, because that's what we put there, you mean?

Jennifer: Yeah. And I think this is mine, because back there - over there - it has a covered vinegar and a not-covered vinegar. Then you have the old vinegar and the new baking soda. So I suppose this one's mine.

Ms. S.: And so that is what?

Jennifer: The old baking soda and lots of new vinegar.

Ms. S.: So that's a little bit of baking soda and lots of vinegar?

Jennifer: Yeah.

Ms. S.: Okay. Jordan, can you sit down, please? Thanks. Okay, thanks Samantha and Robert. So we have some more info on crystals there. Too bad it didn't say what those crystals are made of. So is anybody wanting to take on the question of testing different kinds crystals? Testing different things to see what kind of crystals they make?

Samantha: I will. (Class Discussion, May 15)

When Samantha and Jennifer shared the results of their crystal-growing investigation with the class, Robert was quick to question the relevance of their work. Jennifer was correct in asserting that they didn't really know they would get crystals, but did not provide a clear rationalization for their investigations:

Robert: And what was the point of finding out about crystals?

Jennifer: We didn't really know that we would get crystals.

Ms. S.: Repeat the question, Robert. Is it answered?

Robert: No.

Ms. S.: Then please repeat it.

Samantha: To see what was in the petri dish.

Ms. S.: So, if I put bananas in the petri dish and let them mold, my reason is to see what was in the petri dish?

Samantha: No. Robert's question was, "What is the point of testing crystals?" or whatever. And I said to see what was in the petri dish, because remember that petri dish that we had, and it smelled, like, yuck.

Ms. S.: Did it smell like vinegar?

Samantha: No. I don't remember what it smelled like.

Ms. S.: You just know that it smelled gross?

Samantha: And today we're going to put different things together, like some different stuff, and we're going to mix it and then leave it sit for a while and see if it makes some crystals in the petri dish.

Robert: Yes, but why do you want to find out what's in the petri dish?

Samantha: Because we thought that it was really neat. Like it smelled different, and the crystals looked neat.

Ms. S.: And can you relate it back to what happens when you mix vinegar and baking soda? Because that's our ultimate question. So how is it going to help you understand that?

Samantha: I don't know. Like -

Ms. S.: You kind of mentioned it earlier, but is that what you're asking, Robert?

Robert: Yes. Pretty much.

Jennifer: So, you're wondering why we're doing the crystal thing?

Robert: Yes.

Jennifer: We didn't really know that we'd get the crystals.

Robert: So why were you mixing all these things in petri dishes?

Jennifer: For different tests, but then when it all dried out, we got these strange-looking crystals in our petri dishes instead of what we thought we'd get.

Robert: And now you're continuing the study of crystals and not vinegar and baking soda. You found out that the first two or three made crystals, so why not work on another five or six.

Jennifer: That's what we're doing.

Robert: Yes. And there's really no point to it that I can see.

Samantha: Well, it's kind of a whole class decision, 'cause the last discussion we had, everybody decided to do the crystal thing.

Ms. S.: But why? How is it related to vinegar and baking soda? And we did mention it. It is related.

Rebecca: It was because maybe it's vinegar and baking soda making the crystals. What's left of it might be making it.

Ms. S.: So, if we find out what's left after the vinegar and baking soda react, does that tell us something about vinegar and baking soda? If the point of it is to find out what the crystals are, they should be-

Robert: At least examining them under the microscope.

Samantha: That's what we're doing today, too. (Class Discussion, May 22)

During the following class period, Samantha approached me to ask whether the crystal tests were useful. Both she and Jennifer were now quite uncertain about the point of their work. We discussed how comparisons of vinegar and baking soda crystals with the crystals of the products could help them to understand the reaction, and they went back to work with a renewed sense of purpose. Samantha demonstrated her understanding of this purpose when she added vinegar to a dish full of crystals to see if the material it contained was still baking soda. However, the fact that they needed assistance in identifying a theoretically motivated purpose for their work suggests a less-than-generalized understanding of the importance of this idea.

### 4.3.1.3.3. From "What would happen if...?" to "If..., then...."

A important distinction between the WWHI investigations used by students at Level 2 FOI and those used by students at Level 3 is that students at Level 3 first evaluate whether knowing the results of the investigation thus defined would have any bearing on understanding of the focus question. At this level, predictive implications are often identified, but their identification is dependent upon the evaluation of the plausibility of the premises and the logic of the conclusions that comprise the multitude of what-if questions typical of Level 2 FOI rather than on deliberate attempts to identify predictions with observable implications. This emphasizes the value of WWHI explorations, and is consistent with Clement's (1989b) observation in the following passage:

> Not all generation methods are highly systematic or constrained. The generation of the double-length spring analogy in line 37 provides an interesting example. Here the analogy originates from the idea of sliding a weight along a rod. S2 then imagines this transformation happening on the spring itself, as if it were simply an "interesting thing to try." There is some evidence here that he is exploring new and uncertain directions rather than trying to achieve a specific goal using a conscious strategy of generation under constraints. Although the analogy in this case does not lead to a breakthrough, one cannot rule out the possibility that the ability to think playfully in a relatively unconstrained manner would, at times, be a powerful method. (p. 373)

It appears that the ability to think "playfully" is important to the identification of predictive implications. But if all one does is think playfully, he or she remains at Level 1 or 2 FOI, and the playful thoughts are of little import to explicit theoretical development. When they are evaluated at Level 3, predictions that appear plausible may be used to develop a theory and, if necessary, may be empirically tested. At Level 3 FOI, the relevance of a particular investigation is all that is explicitly recognized. The recognition of the importance of predictive implications that may drive more deliberate attempts to identify them forms the basis of Level 3 IE.

The difference between a useful and non-useful WWHI is based on the critical evaluation of whether the proposed stimulus and / or response is plausible ("Why would that happen?" (WWTH) and on whether the hypothesized effect has any bearing on understanding of the phenomena ("So what if it did?" - SWIID). If a hypothesized effect is not identified, which is typical of Level 2 FOI, consideration of the relevance of the question does not take place.

The following brief excerpt illustrates an idea that could have been challenged with both WWTH and SWIID arguments pertaining to the relevance of an identified WWHI. Jennifer's question regarding whether one end of the battery hardens faster than the other (as it is used up) has implications for the theory she was challenging. However, she did not identify any real reason why one end should harden faster than the other (WWTH), and Frank indicated that even if one end did harden faster, it should not have affect his theory (SWIID):

> Jennifer: What if one end of the battery or energy or whatever hardened faster than the other end?

Frank: Well, then that stuff, because there's a piece of cardboard in there, and that stuff will harden later.

Andrea: But then the energy won't come out of the hardened end, so it can't crash.

Frank: Okay, okay. The light bulb doesn't light without [both sides], so it has to go equal. (Class Discussion, January 6)

In the following dialogue, I encouraged the students to consider the possibility that the particles moving through the wire could create heat energy via friction. At the time of this discussion, most of the students still considered whatever was coming out of the battery to be the energy, and I wanted them to consider an alternative:

Ms. S.: Okay, so say there's, like, electrons. You said they come one after the other, and they keep coming and coming and coming. So here comes millions of electrons, one after the other.

Samantha: It gets got after a while [rubbing hand on arm really fast].

Ms. S.: Could this be happening inside a wire?

Class: Yeah.

Ms. S.: Except this is the wire, and this is the electron, and suddenly, instead of just having to go along this nice cozy little wire with big holes in it, you get to this tiny little wire. So first of all you're going through this really big, big space. It's like you're hitting every now and then, not a lot of friction, but suddenly you have to go through this.

Robert: What if it doesn't go through it…it goes on the outside?

Samantha: How can it go on the outside?

Robert: That's what we're doing with our arms right now, right? We're going on the outside.

Carl: Yeah, but we can't put our hands inside our arm.

Ms. S.: Okay, but I'm suggesting it's going through the middle. Maybe it does go on the outside. But would this be possible if it went on the inside?

Robert: Yes.

Samantha: But how would it go on the outside?

Ms. S.: Okay, can we just leave that for a moment, because, like, what if it did, but what if it didn't? Right? I mean we can say, "what if" all day long, but what if.... Like, can you consider this "what if" for a moment? And if you have a reason to argue with it, great, but if it works.... You know what I mean? Is it possible that the electrons are the things that are moving through the wire, and they go back to the battery? But they are creating heat, which is the energy. The energy is not a particle. The energy is the heat. (Class Discussion, April 6)

This example is interesting in that Robert's what-if is based upon a difference between the hand-and-arm / particle-in-wire analogy. As Carl pointed out, this is essentially a pragmatic difficulty based on our inability to put a hand inside an arm. For purposes of the friction analogy, it does not really make a difference (unless he imagines less friction for particles travelling on the outside of the wire): There would be friction either way. So what if it did? Robert's consideration of the applicability of the analog relationship demonstrates good analogical reasoning skill, but his failure to consider the relevance of the identified difference limited the effectiveness of his argument. It also demonstrates his ability to consider alternatives. Perhaps if I had encouraged elaboration of his idea instead of cutting him off to allow focus on the idea I was suggesting, he would have identified reasons why his alternative was plausible. The momentary focus on a single idea was likely productive, but I should have ensured Robert's idea received due consideration once the plausibility of the energy-inside-the-wire model had been established or refuted.

Numerous examples of cases where arguments based on what-if questions with no identified rationale are scattered throughout classroom discussions:

> Robert: If you took a piece of natural metal out in the middle of the prairie that had never been touched by man and hooked it up to a battery, I don't think that it would.... Like, I think it would still work, though.
>
> Keith: And God put the holes in there from the beginning?
>
> Carl: Maybe God put the holes in the ore, and it's a metal.
>
> Keith: What if he didn't? (Class Discussion, March 11)

Of course, it is possible that he didn't, but Keith has not identified a rationale for refuting Carl's idea (WWTH).

The next case is also indicative of an unfocused WWHI in that Jordan does not appear to have a plausible reason for suggesting the battery might have insufficient shocks. Why wouldn't the shocks last that long (WWTH)? Frank initially addressed the question in this manner, but went on to suggest that if they did not, perhaps the lights would blink:

> Jordan: Well, what if that battery didn't give off enough shocks to last that long?
>
> Frank: Well, it gives off enough shocks for everything. So, it'll just go. It doesn't last that long. Maybe it'll blink, then, when you're doing it.
>
> Jordan: So, that's like when the lights flash in your house.
>
> Frank: Yeah.
>
> Jordan: Okay. (Class Discussion, March 11)

In the next example, the WWHI is based on overgeneralization of the roller-coaster analogy:

Jordan: How can the wire guide it?

Carl: Well, hey. Take a roller coaster, and even if there's a steering wheel in front, it doesn't work, right? Because it follows the track. The wire is like a track. It follows the track.

Jordan: So, if that track just fell apart all of a sudden one day....
(Class Discussion, March 11)

But why would the track suddenly fall apart one day (WWTH)?

When properly evaluated, WWHI questions may provide very productive arguments. In the following situation, Andrea's question prompted Frank to move beyond the isolated case that he was considering to one that Andrea felt should be explicable by the same theory. By asking him to consider a situation in which there is more baking soda, she was essentially asking, "Why would there always be more vinegar?" (WWTH):

Frank: Well, when you pour the vinegar on the baking soda, right? It tries to, like, kill the acid [referring to the baking soda as the acid?]. But then since there's more vinegar, it soaks into the baking soda.

Andrea: What if there was more baking soda?

Frank: Well -

Carl: Then it turns to sludge...

Frank: Yeah!

Andrea: Does it?

Jennifer: Turns into what?

| | |
|---|---|
| Robert: | Sludge. Thick goop. If you look through the microscope, it's the exact opposite. The vinegar moves around, and - |
| Frank: | I know that. That's because there's more of the vinegar than baking soda |
| Robert: | But you said that the baking soda was the one that ate the vinegar. |
| Frank: | I know, but, yeah, it's trying to, but there's more vinegar, so it has a harder time to try, and then the vinegar takes over. |
| Samantha: | If you put two drops of vinegar and two drops of baking soda in, then you'd have the same amount of each. |
| Frank: | It'll turn to goop, because there's the same amount in it. (Class Discussion, April 20) |

Similarly, in the following situation, Frank posed a WWHI question that he felt should be explicable with Jennifer's positives-attract-negatives theory for how vinegar and baking soda react:

| | |
|---|---|
| Frank: | But that still doesn't answer my question. What if you had a negative one in there? |
| Robert: | Then there'd be enough positives to block out that one negative. |
| Frank: | How do you know? What if you had the same amount in? |
| Robert: | Well, then it depends on how much vinegar you put in. |
| Frank: | What if you put the same amount in? |
| Jennifer: | It wouldn't matter. When you put the same amount of vinegar and baking soda in over there, they made gas. Well, when you're mixing them, you have a cup of baking soda and a cup of vinegar. And it would still be the same. (Class Discussion, April 27) |

Although many of the students' arguments demonstrate an understanding of the importance of maintaining a clear focus on the topic of investigation, none of them articulated a generalized understanding of manner in which their WWTH / SWIID challenges led to the identification of predictive implications.

#### 4.3.1.3.4. Using vague theory to identify salient features.

"Maybe it has something to do with…" is a commonly heard phrase when students approach Level 3 FOI investigations with a vague theory. In so doing, they sometimes attempt to determine the salient components of a particular phenomenon prior to developing a more specific theory regarding how those entities might behave. As salient features are identified, they may then be pieced together via imagistic simulation, whereby the student imagines (or draws, or constructs with concrete manipulatives) their role in the phenomenon being investigated. As is discussed in greater detail in Section 4.3.3, this may lead to predictions regarding how the system should behave in certain circumstances, to arguments when these predictions clash with empirical experience, and to broader explanatory power when similarities between visual images and empirical experience are noted. As a result, modification and / or elaboration of theory is very common as students engage in this process. Imagistic simulation is also affected by WWHI formulations, and the manner in which students consider the relevance and plausibility of imagined stimuli impacts the effectiveness of their mental activity.

When students approach investigation on the basis of vague hypotheses, they are essentially working from the parts to the whole instead of from the whole to the parts as they piece together clues regarding how and why certain phenomena take place. For investigation based on vague theory to be classified at Level 3 FOI, students need to articulate a rationale for the identification of each feature they propose as salient. If not, anything qualifies as potentially salient, and the unfocused trial-and-error process that results is highly inefficient. In this study, students sometimes tested the proposed salience of a variable by substituting other materials for the component hypothesized as salient to see if they could achieve the same results. Again, however, they did not recognize this process as a deliberate strategy for identifying predictive implications.

Both Keith and Robert made deliberate and persistent attempts to determine what about vinegar and / or baking soda might account for their observed behavior. Original attempts to do so involved identifying the components of each in an apparent attempt to connect unfamiliar phenomena others that are more familiar. If the components were familiar, the unknown substance may have become more comprehensible. Keith questioned what water, carbon dioxide, and baking soda were made of as if, somehow, this might allow him to relate these substances to their behavior. Rather than assuming that the presence of previously unknown substances was de facto evidence for their salience, however, he then sought evidence regarding which components were most likely responsible for the reaction. He identified vinegar as a member of the broader category of acids, and suggested that this might have something to do with the reaction. However, he eventually selected carbonate as the substance around which he centered his investigations. His rationale for its salience originally centered on his awareness of the presence of carbonate in other substances, but he seemed to have forgotten this as he spoke of carbonate exterminating acid in the following passage:

Keith: It has something to do with carbonate [the vinegar and baking soda reaction].

Ms. S.: Why do you say that, Keith?

Keith: Because I read in an encyclopedia it tries to exterminate any acid, or something like that.

Ms. S.: What? Sorry, go ahead.

Matthew: What exterminates the acid?

Keith: The baking powder, or soda.

Ms. S.: Keith, can you remind us.... The other day you mentioned something else about carbonate. Do you remember when we were talking about.... When was that we were talking about calcium carbonate? Oh, when I brought the.... Remember when I brought the eggs in vinegar? Remember what was happening to the eggs?

All: Oh yeah.

Frank: They were getting soft.

Ms. S.: And did you see bubbles all over the eggs?

All: Yeah. Yeah. Yep.

Ms. S.: Do you know what eggshells are made of?

Carl: Carbonate. Paul did that at home.

Jordan: That was Dan's project a few years ago.

Ms. S.: And he used toothpaste, didn't he?

Jordan: Yep. That protected the egg.

Ms. S.: Oh, that protected the egg. Okay.. That's right. Yeah, eggshell is made of calcium carbonate. Do you hear

> this, guys? Eggshell is calcium carbonate. Baking soda is sodium hydrogen carbonate.
>
> Jennifer: They're like the same thing.
>
> Carl: Carbonate! Cool!
>
> Ms. S.: Okay? And also, did you guys do the rock unit? I did the rock unit with you, didn't I?
>
> All: Yeah, you did. Yeah, we did. Yeah!
>
> Ms. S.: What fizzed? Do you remember?
>
> Jennifer: The fossilized ones. Yeah.
>
> Robert: Yeah, the fossilized ones.
>
> Ms. S.: What do you think? And in fossils, there are shells of things, right? Do you know what shells are made of?
>
> Class: Calcium carbonate.
>
> Ms. S.: Calcium carbonate. (Class Discussion, April 20)

Robert had read that sodium was a particularly reactive substance and pursued a similar line of thought that focused on sodium in place of carbonate:

> Robert: Well I found out that, uh, sodium is a silvery-white material and it's very active. And when it combines with oxygen, so when it's exposed to air, then it turns hard. So when they ship it, it will be like a liquid, but it will get hard when it's exposed to all the air, so they have to liquidize it again. So whenever it's exposed to air, then it will harden.
>
> Ms. S.: Okay.
>
> Robert: So, then I'm thinking that, being as active as it is, anything with sodium in it reacts with acid. And some things have a different kind of sodium in them, so they won't react with the acid, or the acid isn't strong enough to take on all the sodium. And I found that out in salt, and I didn't see a big difference between-

Ms. S.: And why did salt not do that?

Robert: Well I don't know for sure, but I think that the sodium in it is different than the sodium in baking soda.

Ms. S.: And on what are you basing that?

Robert: Uh, because on the salt that I was using it said, "sodium," uh, I think it was "benzid." I can't remember.

Ms. S.: Sodium benzoate?

Robert: Yeah. And in baking soda then it's.... I assume it's different.

Ms. S.: Okay. Just a.... Sodium is.... Baking soda...another name is called sodium bicarbonate, and you're looking at sodium benzoate. Now does that mean that the actual sodium is different, or that it's combined with different things?

Robert: It's combined with different things.

Ms. S.: Did you write down what salt is?

Robert: No.

Ms. S.: Sodium chloride, NaCl. That might be something else you want to consider. So you're looking at the role of sodium, then?

Robert: Yeah.

Ms. S.: Okay. And do you have some tests today that you were planning on doing?

Robert: Yeah. Just anything with types of sodium in them. (Class Discussion, May 11)

Subsequent discussions based on Robert's and Keith's attempts to rationalize their choices of salient properties helped maintain a Level 3 focus during class discussion.

In the following dialogue, Andrea finally began to seek patterns in the results of the tests in which she combined baking soda with a wide variety of other substances:

Andrea: So Robert said that everything that reacts with vinegar has to have sodium carbonate in it?

Robert: That's what I'm trying to find out.

Ms. S.: That's your question?

Robert: Yeah.

Andrea: So how come when you put an egg [whole] in vinegar it reacts?

Ms. S.: Because there's no sodium in egg, you're saying?

Andrea: Yeah.

Ms. S.: Okay.

Robert: But there might be.

Ms. S.: Actually, an eggshell is calcium carbonate. No sodium.

Carl: Maybe it's the carbonate.

Ms. S.: So maybe it's something to do with the carbonate?

Robert: What is in the egg, anyway?

Ms. S.: In the eggshell?

Robert: Yeah.

Ms. S.: Calcium carbonate.

Matthew: That's all?

Ms. S.: Basically. That's the main thing. And plus, if sodium is so reactive, why does it react so strongly with baking soda? Or sorry, with vinegar, and yet vinegar reacts so weakly with salt.

Robert: Maybe because there's not as much in it.

Ms. S.: Less sodium, you mean?

Robert: Yeah.

Ms. S.: Okay. Questions for Robert's sodium theory guys. Questions, thoughts, ideas.

Robert: Maybe something in the hen or the egg or something on the egg is maybe sodium.

Andrea: Okay. Then I have a whole bunch of lists here, like, what worked and didn't work, and a squeezed lemon with milk reacted. It didn't fizz like baking soda did, but when you put it to your ear you could hear popping.

Ms. S.: Okay.

Robert: Uh, it says that, also in the dictionary, that sodium is in many things, too. It's one of the.... All the things that are in baking soda and vinegar are very important elements to the earth. And pretty much everything on the earth has some of these elements in them. (Class Discussion, May 11)

In the next segment, Andrea identified a distinction between the behavior of baking soda and baking powder, and then tried to identify what characteristic of the substances might be responsible for this difference. This signifies a significant advance over her original strategy of testing baking soda with as many other substances as she could:

Andrea: Is there something that baking soda has that baking powder doesn't? 'Cause baking powder just goes slow, and baking soda shoots up when you mix it with....

Ms. S.: When you mix it with vinegar?

Keith: [looking into microscope] Wow! Those are so small!

Ms. S.: [speaking to Andrea] Okay. Check your ingredients. The baking soda box should have ingredients on it. [to the class] Andrea's going to check the ingredients on her box tonight.

Matthew: What's the difference between baking soda and baking powder?

Keith: Baking soda is in baking powder…

Ms. S.: Yes, it is.

Keith: I read that. (Class Discussion, April 20)

After identifying certain features as salient, students need to determine the manner in which these components could interact so as to produce observed effects. In some cases, the identification of certain components prompts analogies that provide a broad structure in which to incorporate the pieces. In others, the components are mentally manipulated in a manner that produces the necessary outcome. This, too, often involves analogical reasoning in that the behavior of the pieces is based upon the behavior of those pieces in familiar situations or upon similar pieces in other situations. Typically, there are many ways that a collection of salient pieces could be manipulated to generate a desired outcome, and the plausibility of their behavior then needs to be considered. It is in this context that the ad hoc tendencies that Robert identified as a concern (see Section 4.3.3.2.2) come to the fore.

#### 4.3.1.3.5. Verification.

Students at Level 3 FOI are able to generate evidence for or against formulated theories, but do not understand the need to attempt systematic disconfirmation of their ideas and tend to seek evidence in their favor. Self- and peer-questioning of proposed theories may be fairly stringent, but is not based on an understanding that a theory can never be proven.

During her battery interview, Samantha very deliberately tested her ideas, but eventually used the rejection of one of her models as de facto evidence for another.

In the following situation, she considered the implications of a battery model with one side that is full of energy and one that is empty until it receives used energy particles:

> Samantha: Yeah. This is pulling, and this pulling more. So they're, like, pulling, and then they come here, and this is letting it go sort of like. So it lets it go, and then it's attracted to here, and then it'll be attracted to the bottom of the battery, and then it'll go through here, and then all the bad stuff is in here, so all of the bad stuff will be in this battery. Well, there would be good stuff, too I guess, but there'd be no bad stuff in this one [indicating on her diagram the battery in series to which the positive wire is attached]. So this one is, like, good still, 'cause the bad stuff hasn't gone out. So, okay, it pulls the plus out of here, like, some of the plus ones, and then some of the plus ones from here, and they go up through here or into the light bulb, and then they go here, and they turn into base. So then it goes all the way back, and then the next main force, like, almost right here is a magnet sort of, too, that doesn't like it. So it pushes it away sort of, and then it goes back through here and into this one, and then into this, and then this would be mainly bad particles in this battery [the battery in series to which the negative wire is attached], 'cause it would have all the bad stuff from both of these things - have all the bad stuff in here. But I don't really know how the bad stuff would get back into here. Maybe, if it stays here, then none is in here, then if you take this battery, and, like, after you've used it for this or whatever, then next time you go to use it, it only has good particles in it now, because there's no bad that have come back into it. Are you with me? (Battery Interview, March 30)

Samantha clearly developed parts of this explanation as she made a mental journey around her circuit. However, when the particles she was envisioning returned to the battery, she noted a discrepancy: All of the bad particles were in one battery. At that point, she stopped and tried to figure out an explanation that would address this stumbling block in her theory. Her ability to note this discrepancy was based on the implausibility of the picture that formed rather than a deliberate attempt to disconfirm her theory.

Later in the interview, I challenged Samantha's full-side / empty-side battery model by asking her why you couldn't just hook the positive terminal of one battery to the negative terminal of another. I also asked how two batteries in series would work if her model were accurate. She then developed an alternative model in which all of the negatives and positives were inside protective bubbles mixed throughout the battery, carefully articulated implications for each model, and tested them empirically. She eventually rejected her empty-vessel battery model, but again, this was due to an implausible mental picture:

> Samantha: Okay, so there's one and there's one [connecting two batteries in series with an ammeter]. That's two. Let's see what this tester thing does. Yup, it seems to be working. That one seems to be working. So this theory is wrong [marking the full-side / empty-side model on her diagram]. So if this one [the bubble model] is right, I should be able to.... So then this theory doesn't work on this one...[thinking and examining her batteries]. But it's still.... It's just hooking this up to this. That's all it's doing. But if this theory is right, if I take this, and all you need is this side and that side, then you should be able to go like that [marking on her diagram]. But you can't. So I guess, then that kind of means...[thinking and drawing]. But for this one, this means just hooking this up to this. And then for the same thing for it to turn into base, it would just go, like, if it were two batteries, it turns into base and stuff, if it were two batteries [making a new diagram] A, B. A and B. You have a nice pen!!
>
> Ms. S.: And what are those X's?
>
> Samantha: That's coating on the sides.
>
> Ms. S.: Oh, okay.

Samantha: And then, there are six good things. First we started out with however many little things out of acid in here, then it goes out through here when we hook the wire up, then it goes into here and lights the bulb, and it comes through here and back into the bulb and turns into base. It is now base. I'll make a squiggly line for that one. Then it comes through here, and it goes into there, and there are those six that were in here have all turned into.... Whoa! Hang on! If I lost six, then the battery should be dead first time I use it. If I had six acid in here, and it takes all six at the same time and all six go back in, then the battery's dead. (Battery Interview, March 30)

The following dialogue clearly illustrates Samantha's tendency to verify rather than disconfirm as well as her belief that a theory can be proven. She used her rejection of the full-side / empty-side model as evidence in favor of her bubble model:

Samantha: The bulb's okay.... We can't test that other theory.

Ms. S.: Test which one?

Samantha: This one [pointing to diagram]. The dots one. [hooking up the batteries in a different way; bulbs light]. That's right for sure.

Ms. S.: Is it right for sure, or is it just not wrong? Or sorry, how come that proves that this [pointing to diagram] is right?

Samantha: Well, because, well this one didn't work, so this theory's wrong, so there's no two halves. At least with a 6-volt there isn't. And if you have a 6-volt doing that, which is pretty much the same thing, then it sort of proves it's right because then you hook the positive up to the negative....

Ms. S.: So, does this prove that there is acid and base inside? [mixed throughout the battery, as her bubble theory suggests]

Samantha: Yeah. (Battery Interview, March 30)

In other words, because one was shown to be implausible and the evidence gathered so far was consistent with the other, that one must be right.

During her battery interview, Samantha did a very good job of continuing to develop her battery model. However, she tended to marshal evidence that supported her theories much more effectively than she found counter-instances in which they did not work. When either the other students or I pointed out discrepancies in her model, she took them seriously and worked hard to explain them or to modify her theories. Nevertheless, she seldom came up with these on her own. She did seem to be very aware of this and identified other people's arguments and questions as vital to the effective development of her battery model. This knowledge seemed to help her to develop a clearer understanding of the importance of self-questioning. At the end of her electricity interview, she made the following comments:

> Ms. S.: ...As you were doing this, were there any things that helped you get ideas? To develop your ideas here?
>
> Samantha: Other people's batteries. Like, Jennifer had the mixing kinds, but I thought that.... Like, she had two different acids mixing, but I thought maybe I should have them in just separate compartments. So then it definitely would not be a short circuit. So, it would be hard to argue against and say it was a short circuit, 'cause the two acids wouldn't be mixing.
>
> Ms. S.: So you were thinking about other people's arguments when you made it?
>
> Samantha: Like Robert has some really good arguments, so I was thinking, like, if I could have something to say, not just like sort of stand there in front of the class and be, like, "Umm...." I wanted to know my battery better.
>
> Ms. S.: Was there anything tonight as you did these that helped you to come up with ideas or ways to improve your battery?

Samantha: Well, your question about hooking up from the top of one battery to the bottom of another battery. Well, that didn't work, so that kind of changed my mind on that one, so I didn't like that one anymore, 'cause it didn't really work. It didn't light up.

Ms. S.: Were any of your questions helpful?

Samantha: Well, the one of how this would go through both of those, and how would it go through there [two bulbs in series]. It made me think more.

Ms. S.: So, by making a new situation.....?

Samantha: Yeah. Like, I was wondering how those would go through there, and then I thought maybe like a magnet, a force was pulling it or something. Then it could go through there and come back. And then the density thing we did in science a couple of years ago. Remember we did that density thing. We did the density unit. That sort of helped me, too, to think of that would be more dense inside, it would be more heavy. And this would be, like, not as dense. (Battery Interview, March 30)

Frank also recognized the value of others' questions in the development of his battery model. As in Samantha's case, his comments indicated that such questions help him to move toward a correct answer. He did, however, clearly indicate that such an answer remained elusive:

Frank: Well, I think it's sort of like between. Like, you'd have to have more stuff in it for proof. Like more ideas on it.

Ms. S.: On this one?

Frank: Like more ideas on both to prove it.

Ms. S.: So, you're not ready to make a choice is what you're saying?

Frank: Yeah, so it could be that one or that one. (Class Discussion, March 16)

He also admitted that it was very difficult to choose, because new evidence kept making one or the other look preferable:

Frank: And it helps, too, when people ask you more questions. 'Cause then you get to think on it, right? And you'll get your more proof. And when people keep asking you more questions, but the bad thing is they'll keep on asking you questions about that one and this one and they'll have [no?] proof still.

Ms. S.: So, it's hard to get one looking better than the other.

Frank: So, one day, we'll have this one better than the other one, and the next day, that one will be better than this one. And then maybe they'll be the same again.

Ms. S.: Could you take parts of one and parts of another and build one that uses the good stuff out of both of them?

Frank: Yeah. So that's sort of like you doing the second battery with Andrea's, so like, you're using some of these ideas and putting them in there.

Ms. S.: You mean like this one?

Frank: So you're using these ideas and putting them in there, 'cause if we use this idea of pushing it, right, we're using that idea, and then we're using the magnet where it pushes and where it sucks in on the negative side. So, it's like using the same ideas. There's not much of a difference.

Ms. S.: Between?

Frank: You're using the same ideas on this one and that one.

Even Robert, who explicitly commented that he had great difficulty criticizing his own ideas, recognized the value of others' questions in helping him evaluate his battery. Although each of these students recognized the value of argument, none recognized the importance of identifying implications that could disconfirm their theories.

#### 4.3.1.4. Level 4: Metatheoretically grounded disconfirmation.

By Level 4 FOI, students must come to appreciate systematic disconfirmation as a necessary control on the observational bias that is built into the way we think and the resulting subjective nature of the knowledge that we construct. The understanding of this subjectivity likely develops only when extensive reflection on the theory-building processes evident within all three main frameworks (FOI, AR, IE) makes this more apparent. Level 4 FOI requires not only the explicit awareness of the role that theory plays in driving investigation and observation that is developed at Level 3, but also an understanding that the knowledge thereby developed is dependent upon the theory that drove it and that it could have been developed in many other ways. At this stage, the confirmation strategies evident at Level 3 are replaced by a systematic questioning of proposed theories that demonstrates attempts to determine other ways that a particular phenomenon could be explained. Appreciation of the importance of previous ideas in driving the investigations that allowed the development of new understandings is also developed at this level.

Although none of the students in this study have fully reached Level 4 FOI, I believe it is important to include as an attainable goal. Such a goal is based on extrapolation of Level 3 FOI by the process of reflective abstraction on isolated instances of Level 4 strategy-use within familiar domains, and on evidence from the literature. Carey et al's (1989) formulations are consistent with the types of scientific activity engaged in by students classified at Levels 1-3 FOI, so it seems plausible that their highest level would be commensurate with one extrapolated from their Level 3 criteria. Reflection on the role of the theory that guides Level 3 FOI could make apparent that the observations that are already directly associated with a guiding theory at Level 3 are in fact dependent upon that theory. Such recognition emphasizes the subjective nature of knowledge and emphasizes the need for systematic disconfirmation. Recognition by students at this level of the "cyclic, cumulative nature of science as the construction of ever deeper explanations of the natural world" (p. 53) could also be a logical outgrowth of the Level 3 recognition that an explanation can always be challenged with another, "Why?" There is limited evidence that this realization is beginning to dawn on some of the students in this study. There were times when Carl identified frustration with his inability to prove his ideas, but this seems more rooted in a belief that it is impossible for him to determine whether his ideas are accurate, because he does not have and / or cannot identify the necessary means to test them. At times, this belief appears to prevent him from making honest efforts to evaluate his ideas, and therefore from progressing to Level 4 FOI. Learning to seek predictive implications seems to be a critical component that could help Carl work toward this transition. This is discussed in greater depth in Section 4.3.3.2.3.

#### 4.3.1.4.1. Understanding the subjective nature of knowledge: The need to disconfirm.

The distinction between knowledge unproblematic, which deals with "one objective reality" and knowledge problematic, whereby "theories are judged to be more or less useful, not right or wrong" (Carey & Smith, 1995, p. 54) provides a useful distinction between Level 3 and Level 4 FOI. These categorizations were made on the basis of interviews with scientists. Carl's comments suggest that he had little faith that his own theories could be proven, but he did not recognize the applicability of this understanding to the broader realm of scientific knowledge. For the most part, he still seemed to believe that someone else knows.

Inclusion of a fourth-level category is also consistent with Moshman and Lukin's (1989) categorization of students' understandings of the nature of knowledge:

> Further reflection on the subjectivity of knowledge yields an increasingly explicit distinction between theory and data, including the Stage 3 concept that theories are purely hypothetical and must be tested by gathering data that could disconfirm them. This is a metatheoretical view and can itself become the object of further reflection leading (at Stage 4) to explicit conceptions of metatheories and their relation to theories and data. (pp. 194-195)

The results of D. Kuhn's (1996) study regarding the theory-evidence coordination strategies of adolescents, young adults, middle-aged adults, and older adults also implicate metacognitive competence as an important difference between what I have termed Level 3 and Level 4 FOI. She noted that many of her subjects were able to make inferences that coordinated theory and evidence, but that most did so inconsistently and instead selected evidence within a multivariate setting that tended to confirm their initial ideas:

> ...subjects must be able to reflect on their own theories as objects of cognition to an extent sufficient to recognize they could be wrong. Second, they need to recognize evidence that could disconfirm the theory. Less competent subjects do not conceive of the possibility that theorized relations are wrong and avoid evidence capable of disconfirming them.... Not only must evidence serve as the basis for evaluating and possibly revising theories, but theories legitimately influence the direction and form of investigation. The difference between skilled and unskilled reasoning lies in the degree of control that is attained of the coordination process (Kuhn, 1989). Without such control, beliefs come into contact with new evidence in an unstable way. Evidence is either ignored or distorted to protect the belief, or the individual is unduly swayed by it, leaving beliefs at the mercy of transitory, unpredictable external influences. In contrast, those who have achieved control of the interaction of theory and evidence in their own thinking are able to distinguish what comes from

> their own thought and what comes from external sources. They exercise this control because they are able to think *about* their theories, not merely *with* them. (p. 275)

However, as in this study, Kuhn did not observe skilled thinkers in this category. Her comments are based on her interpretation of what would be needed to remedy the fallacies in the thinking of the subjects that she did observe. Further longitudinal work is needed to monitor the development of epistemological understandings favoring systematic disconfirmation.

With increased participation in activities that promote authentic scientific thinking and increased reflection on the nature of that activity, it seems likely that students could attain deeper epistemological understandings of the nature of theory as something that cannot be proven or verified. This could then lead to recognition of the need for systematic falsification. In this study, many students did attempt to falsify each other's theories, but it appears that an understanding of this process as necessitated by the epistemological status of a theory was, at best, only beginning to emerge. Most of the students either enjoyed the game of proving each other wrong and only argued when theories did not match their own ideas or argued with the aim of reaching an ultimate level of truth. This certainly helped to promote highly effective debates and encouraged the students to look more deeply at the nature of various theories, but it would be misleading to imply that their conscious and systematic attempts to debunk each other's ideas indicate a deep understanding of the subjective nature of scientific knowledge. It is, however, a necessary stage upon which they may be able to reflect as a means of developing such an understanding.

In the following dialogue, Carl's comments demonstrate an emerging understanding of the need to disconfirm. He noted specific instances that his theory was able to explain, but was clearly aware that further evidence could refute his ideas. His frustration with this understanding is quite evident in his comments:

Carl: Because there's zillions of ways that you could, that one person could think of, that explain why or how these two things [vinegar and baking soda] mix or what they do when they mix. And this is just one in a sea of zillions, so it could be right, it could be wrong, it could be a little bit of both.

Ms. S.: So how do you think a scientist would have to go about, like from this point, what would you have to do?

Carl: Go with the idea until you can prove it wrong.

Ms. S.: So can you think of a way that you might test it so that you can find out of it's wrong?

Carl: Uh, I don't know. Everything goes with my theory so far. The tests about the baking soda, or the $CO_2$ gas, carbon dioxide that is. And, um, I don't know. We'll have to wait until the crystals dry of Samantha's and Jennifer's.

Ms. S.: And how will that help you?

Carl: Well, if all the vinegar is left, then part of my theory is wrong.

Ms. S.: Because you're saying the vinegar breaks?

Carl: Yeah.

Ms. S.: Okay.

Carl: Because it says in here that the NaH combines with what's left of the $CH_3COOH$ - the vinegar.

Ms. S.: Okay.

Carl: What's left of it. And I'm saying that I don't know if it breaks or not. I'm assuming it does. (Chemistry Interview, May 25)

Although Carl was willing to accept the notion that he needed to try to prove his idea wrong, he was frustrated by the idea his ultimate goal would always be to seek mistakes in his work:

Ms. S.: Okay, so it's interesting, and I'm sure there are lots of scientists in the past who have wanted their ideas to be right and never challenged them. But, eventually, there is usually someone who comes along and does what?

Carl: Proves them wrong.

Ms. S.: So, would you rather have someone else challenge you, or would you rather do it yourself?

Carl: I'd rather have somebody else find a flaw than me.

Ms. S.: How come?

Carl: Because I like being right for the time being. (Chemistry Interview, May 25)

In the following passage, Carl identified "going through all the possibilities" as one strategy for generating accurate ideas. This may have been a productive context in which reflection leading to greater awareness of Level 4 FOI could have been based. He may not find a way to prove that his ideas are right, but by sifting through the possibilities, he could attempt to find the one that is most rational:

Ms. S.: So, what do you do? When you think directly about it, how do you search for an idea?

Carl: Go through all the possibilities. All the possibilities of what could happen. Like, when I thought of this new battery, I'm like, "Well, I don't want that many arguments, and I want one that will work fairly well," and I came up with one that worked. Totally awesome. And I spent maybe ten, fifteen, maybe five minutes on

> it, and I still had five minutes to go out and play. So, maybe I spent five minutes on this battery, and I spent maybe two months thinking about it. And some of them come to me in my sleep. I have no idea how or why. (Battery Interview, March 25)

Carl's awareness of the need to consider multiple possibilities does not necessarily indicate an explicit understanding of the subjective nature of knowledge, but is a step in the right direction. His response to my question about how a scientist might approach his difficulty was cliché and likely represented little more than a superficial understanding of subjective knowledge. However, Carl's identification of evidence that his theory could explain suggests that the frustration evident in Carl's comments may involve more than an inability to identify testable implications.

How to effectively challenge students' ideas regarding objective knowledge remains an open question. Reflection will almost certainly play an important role, but more direct metacognitive challenges of the sort identified by Gunstone (1994) may also be necessary. These are discussed in Section 4.3.3.2.4.

#### 4.3.1.4.2. The foundational importance of old knowledge.

> *Generative inventiveness, or the ability to replace and repair what one removes, gives one the confidence or assurance to be critical of and to tear down, at times, existing ideas. S2 [the primary focus of his study] seems willing to consider "risky" analogies, such as the double-length spring and the bending rod, that appear to be very different from the original problem.*
>
> (Clement, 1989b, p. 375)

Starting points for analogs were highly diverse among the students observed in this study. Highly productive ideas were generated from very different starting analogs, sometimes to describe the very same phenomenon. It is this that allowed the students to make substantial progress from diverse beginnings by capitalizing on their own knowledge. Understanding this could be a critical factor in maintaining motivation in the face of the realization that a developed explanation needs to be rejected. This is not an area in which I encouraged student reflection, but is one that could have provided a rich context for this type of reflection. It seems likely that upon re-considering the development of their battery or chemistry theories, the students could have come to recognize the important role that their old ideas played in helping them progress to the ones that they had developed by the end of the unit. Perhaps this would have helped to prevent the sense of hopelessness demonstrated by Carl during the culminating days of the chemistry unit.

### 4.3.2. Understanding the role of analogy (AR).

> *The task of science is both to extend our experience and reduce it to order, and this task presents various aspects, inseparably connected with each other. Only by experience itself do we come to recognize those laws which grant us a comprehensive view of the diversity of phenomena. As our knowledge becomes wider we must always be prepared, therefore, to expect alterations in the points of view best suited for the ordering of our experience.*
>
> (Bohr, as quoted by Hawkins, 1990, p. 100)

Prior to elaborating on the ways in which children engage in analogical reasoning, it is important to reiterate and clarify the differences between what I have chosen as a definition of analogy and the more narrowly focused definitions prevalent in much of the literature. Attempts to distinguish analogy from other relational structures by means of labels such as "literal similarity" or "application of an abstraction" (Gentner, 1983, p. 155) are arbitrary and unnecessary in the context of the current discussion. Clement's (1988) exclusion of surface similarities, parts of larger systems, extreme cases, and cases at different levels of abstraction may at times be effective in distinguishing between relationships that are or are not analogous, but are unnecessarily restrictive. For the current purposes, they merely confuse the sole point of importance, that being whether explanatory structure is transferred from one situation to another. Any relationship that identifies similarity between two or more elements, be it example or extreme-case, within or between domain, needs to be perceived as such before it can be processed as such. It cannot, therefore, be classified simply on the basis of static characteristics. The classification of a piece of information as an example is entirely dependent upon its place in the web of an individual thinker's mind, as it is this placement that makes possible (or not) the transfer of explanatory structure that is analogical reasoning. Vosniadou (1989) distinguished "static similarity" from "the process of reasoning by analogy" (p. 415), but continued an attempt at what she admitted was a hazy distinction between "within-domain" and "between-domain" analogies:

> The distinction between within-domain and between-domain analogical reasoning is not a dichotomous one. Rather, it represents a continuum from comparisons involving items that are clear examples of the same concept to items that belong to different and remote domains. (p. 415)

I wish to make a stronger point: Domains themselves cannot be based on static definitions, and any attempt to do so is necessarily bound by the relational properties that exist in the mind of the individual doing the defining. At the moment that an analogical relationship is perceived between two or more phenomena, either elements within them or reductions of the broader relational structures comprising them become one and exist as identical relations. In other words, when a domain is defined by connections that are in accordance with the thought patterns of an individual person, reference to analogical reasoning as "between-domain" becomes circular. All analogies cross a domain of some sort. The size of the jump is always the same in that it merely represents the recognition of identical features, which may be evident at a concrete level or at some level of abstraction. This idea is discussed in greater detail in Appendix I.1.

The examples that follow help to clarify the importance of the proposed definition of analogy in that they (a) demonstrate the difficulty that may exist in transferring explanatory structure between what, from a domain-perspective, would likely be classified as "within-domain" situations and (b) emphasize the relevance of examples as possible sources of explanatory structure for broader relations.

By most standards, the recognition of similarity between a wet cell and a dry cell or between a flashlight battery and a dry cell would classify as a within-domain analogy. Even so, many students demonstrated an unwillingness to transfer explanatory structure among these structures. Although the students commonly referred to all three as batteries, they were sometimes reluctant to assign them a common explanatory structure. As a result, anomalies that would have thus been made apparent were not recognized and were not used in the evaluations of their models.

An interesting example of this is evident in Samantha's consideration of whether a 6-volt flashlight battery operates in the same fashion as a 1.5-volt C-cell. The following discussions demonstrate attempts that she made to judge whether it would be appropriate to transfer explanatory structure from one to the other:

> Samantha: Oh, I have a question. In Rebecca's book, right here, it's both. In here, it's connected to the top and the bottom in the picture [the cell in Rebecca's book was cylindrical, but had both terminals located on the top].
>
> Ms. S.: And why is that?
>
> Samantha: Because they mean the same thing, like in the 6-volt battery, the big one, they're both on the top, and they're both negative and positive, too.

Ms. S.: So then do you agree that what Jordan drew is exactly the same as what's in Rebecca's book only with our kind of battery?

Samantha: Yeah. (Class Discussion, January 6)

During her battery interview, she was not as confident in the similarity between a flashlight battery and a C-cell:

Samantha: But I don't think there's any [C-cells] that really work.

Ms. S.: Would it have to be a C-cell?

Samantha: I don't know.

Ms. S.: Could you go from the full side of a 6-volt to the empty side of a 6- volt? [This question refers to the battery model developed by Samantha in which energy from the 'good side' of a battery travels around a circuit and returns to a 'bad side.']

Samantha: I don't know. I haven't really thought up a 6-volt battery yet.

Ms. S.: Would the positive and negative be the same type of idea? Or no?

Samantha: Yeah.

Ms. S.: Could you test this idea, like go from positive of one to negative of another [drawing a diagram]?

Samantha: [drawing a diagram] Maybe a 6-volt could be like this. These are C-cells, so this is the plus and minus. Maybe, like, the 6-volt has.... This is the plus, and this is the minus. You have another 6-volt.... This is the plus, and this is the minus with things down the middle [continuing to draw as she speaks].

Ms. S.: Okay. So how would you test this with a 6-volt?

Samantha: You'd go from this one to this one [pointing to diagram].

Ms. S.: Like from here to here? [drawing on diagram] Should that be about the same as this?

Samantha: Yeah.

Ms. S.: Is there a 6-volt that works?

Samantha: [looking for battery] Here, I'll try these two. Where are the alligator clips?

Ms. S.: Oh, um.... Is there a bag full of them right there? I think that bag right there is full of alligator clips. In that black and red one? No? Oh, they're in the buzzer box in the bottom part.

Samantha: We should only need one, right? Oh, two, if we're going to hook them both up. (Battery Interview, March 30)

Subsequent comments reveal Samantha's uneasy acceptance of similarity between a C-cell and a 6-volt battery:

Samantha: Well, because.... Well, this one didn't work, so this theory's wrong, so there's no two halves, at least with a 6-volt there isn't. And if you have a 6-volt doing that, which is pretty much the same thing, then it sort of proves it's right, because then you hook the positive up to the negative.

. . .

Samantha: [thinking] No.... Except for, like, all of the ones that I've thought of [drawing a new diagram], if you had your battery.... I guess this goes for both of the batteries.... What if you hooked another battery up to it, like the same type of battery?

The association that Samantha was able to make between the flashlight battery and the C-cell was based on their observed effects in a circuit and the fact that both have a positive and negative terminal which need to be attached for the circuit to function. Although other factors may also have been involved, the reduction of the battery / cell principle to these core principles allowed her to transfer explanatory structure, if hesitantly, between them.

Keith's original battery model consisted of a lemon with electrodes, which he had seen in a book sometime previous to our discussion. Frank questioned the equivalence of the lemon battery to a C-cell with the following written argument: "Lemon Juice is like battery Juice and battery Juice stings So why dosent Lemon Juice sting to?" Keith wrote back: "It dosen't sting it itches." Frank disagreed: "Lemon Juice dosent ich does it." Keith conducted a poll: "Yes! everybody said so!" and also reminded Frank that "When you took apart the battary and you got liquid on you it iched didn't it!" They did not resolve their argument, but their attempts to determine the equivalence of the proposed analogs are very evident here. During this process, they also articulated a preliminary understanding of some of the properties of acids.

At the end of the electricity unit, I provided the students with a summary of the arguments and questions elicited by different battery models (see Appendix D.2). Even then, the equivalence of the different types of cells and batteries was questioned by the students. Clearly, their definitions of batteries had not been reduced to a core set of defining properties that would allow them to be connected in the students' minds:

> Samantha: Okay, and it's seven down. And it says that some people were talking about the energy getting hard after it was used. Why is this necessary? Also, it didn't happen in the wet cell or the lemon [paraphrasing written argument]. Well, in the wet cell it didn't, but in the lemon it did, because the lemon dried up.
>
> Ms. S.: Is that because of the reaction?
>
> Samantha: It was exposed to the air?
>
> Ms. S.: So is that because of the battery, or is that because of the air? What do you guys think?
>
> Class: Air.
>
> Keith: It was exposed to the air, so most of the moisture got out into the air.
>
> Samantha: If you broke a battery open, when the moisture got exposed to the air, wouldn't that dry up, too?
>
> Ms. S.: They did. But do we break batteries open to use them?
>
> Class: No.

Frank: And Robert said batteries already have liquid in them, right. So, like this one, this looks like paste instead of liquid, doesn't it?

Class: Yes.

Ms. S.: So, is it totally dry?

Class: No.

Matthew: It isn't dry and it isn't liquid.

Rebecca: Because there's a covering on top of it. It's like there's a plastic covering on top of it.

Matthew: Okay. I've got something. Well, then why do they say that batteries leak?

Ms. S.: Do some batteries have liquid in them?

Robert: When they leak, it's like a slime. It's not like a liquid. It's like a slimy stuff.

Jordan: Yeah. It's like a white slime.

Ms. S.: Could the liquid come out of the paste?

Class: Yes.

Ms. S.: So, does it need some kind of liquid? Like, whether it's in paste or totally loose?

Matthew: It needs some liquid. (Class Discussion, April 3)

One instance that clearly demonstrated the importance of the idea that situations must be perceived as alike before explanatory structure can be transferred between them took place as the students proposed and debated different circuit arrangements that could be used to wire burglar alarms to different rooms in their model houses. Initially, all of the ideas appeared very different. As they began to debate the pros and cons of the different arrangements, however, they noticed that some of them were exactly the same:

Ms. S.: Okay, just for the last few minutes here, guys, some of these.... You know how Carl's circuit, the one I just erased, it was kind of like this [drawing on chalkboard]. And then there was a light bulb here, and then another light bulb here, and these were all kind of hooked together neatly like that. Do you remember how he said that was exactly the same as Rebecca's? Do you think this one could be drawn more simply? So you don't have to have wire jumps? It's very clear, because the wire jumps make it very clear. How should we do it, Jordan?

Jordan: You could erase this and go around here to here...

Ms. S.: So, take this....

Jordan: Take this wire.

Ms. S.: Can you guys listen up so you know whether you agree with this or not?

Jordan: Take this wire and go over here and touch this wire.

Ms. S.: So, instead of crossing here, would that still be the same thing? He wants to take this wire right off, and instead of connecting to this part of the negative wire, go around and connect to this part of the negative wire. Anybody else disagree?

Carl: I don't disagree, but then you could take this wire off, and then bring it around to here.

Ms. S.: And then.... So we don't have any overlap? Okay. That is interesting how you changed.... You know what, let's even try to straighten this out a little bit. Let's start with the battery [drawing on board] and from the negative end, where do we go first?

Jordan: You go down to the first....

Ms. S.: To the sides of the bulb? Okay, let's put a bulb in here. And does this bulb also connect to the positive end of the battery?

Class: Yes.

Ms. S.: Right away, or does it have to go through another bulb?

Jordan: It needs to go through another bulb.

Class: No.

Ms. S.: Does it? From here to here?

Class: No.

Ms. S.: So it's directly connected to the positive, isn't it?

Class: Yes.

Ms. S.: Okay. So, is that still okay? So we've taken care of this bulb, right? Now this bulb is connected to another bulb. Is this the positive side or the negative side?

Class: Positive.

Ms. S.: So this positive side is connected to another bulb. Is this bulb connected to the negative end directly?

Class: Yes. No. Yes.

Ms. S.: So if we just put one here, does that have a direct path to the negative bulb?

Class: Yes.

Ms. S.: And now this bulb is taken care of. Now how about this one? Does it go straight to the negative?

Jordan: No.

Robert: This one looks exactly like Carl's.

Jordan: Just the extra bulb.

Carl: Hey, you connected that to the positive one.

Jordan: Hey! That's drawn like Carl's.

Ms. S.: Keep that circuit diagram page, Samantha. Just flip to.... Does that look kind of like how these were drawn?

Class: Lots.

Keith: What is Carl's?

Ms. S.: Carl's is this one. Isn't that neat how you can untangle your wires?

Jordan: And make it exactly the same as everybody else's.

Ms. S.: Well, it's not exactly, but it's surprising how many of them are the same, and we just didn't realize it. Because were Carl and Rebecca's really all that different?

Carl: No, they only have one more light bulb.

Robert: And that one's exactly like Samantha's. Then that one's exactly like Rebecca's. And Carl's is like Samantha's.

Matthew: And you can organize Samantha's just the same way.

Ms. S.: Jordan, do you want to come and untangle the wires on Samantha's?

Robert: And I'm sure one of Frank's matches Rebecca's.

Ms. S.: Watch carefully to see if you agree, 'cause you have to-

Jordan: This -

Ms. S.: He's taking the positive wire to that bulb off, but you still want it to go there, just without overlapping. So, did he do it without changing it? Do you think so, Samantha?

Robert: He changed this from there.

Ms. S.: Except she had it straight to the knob, okay. Frank?

Jordan: There, now they're untangled.

Ms. S.: Now, is that really any different than Rebecca's?

Class: Nope.

Ms. S.: You have three bulbs that are directly connected, so really Samantha's and Rebecca's are exactly the same.

Keith: And Carl's is the same, too.

Ms. S.: And Carl's is the.... The only difference is one less bulb, right?

> Carl: I should have had a motor or two for that one, and then it would be like this one. (Class Discussion, January 9)

In moving beyond the superficial differences imposed by the tangled wires, many of the students were able to recognize common properties that united certain circuits. The reduction to salient features evident here is essentially no different at this level of abstraction than it would be at one that Vosniadou (1989) might consider "cross-domain" (p.415). It was equally essential for enabling the transfer of explanatory structure.

Although Clement (1988) did not recognize examples as analogies, it seems that the only difference between generating an analogy via a broader principle and using an example as a source of explanatory structure is the direction that you have to move in a mental hierarchy to find an appropriate source analog. As the students attempted to unpack abstractions such as "chemical reaction," "neutralize," and "energy," they sought explanatory structure from examples to clarify vague definitions of apparent wholes. In these cases, evaluating the applicability of the analog relationship involved using the explanatory structures of examples and counter-examples to clarify and re-define the wholes. This is quite evident in the following discussion, during which the students attempted to define "chemistry":

> Matthew: Where you usually take some chemicals and you mix them to see what happens.
>
> Ms. S.: Sometimes. Yeah? What else. Robert?
>
> Robert: That's about what I was going to say.
>
> Ms. S.: Okay. Uh, Carl.
>
> Carl: Mixing two or more different chemicals to make something different.
>
> Ms. S.: Okay. Uh, Samantha.

Samantha: Um, maybe an example of chemistry or something would be, um, vinegar and baking soda.

Ms. S.: Okay. So, what do you mean? That's an example of -

Samantha: When you mix them together.

Ms. S.: Okay.

Samantha: Like, what your reaction is.

Ms. S.: And what happens that makes that chemistry?

Samantha: Like, it fizzes.

Ms. S.: Okay.

Robert: Something happens when you mix them together.

Matthew: Something unusual happens.

Ms. S.: Something unusual happens?

Matthew: Yeah.

Ms. S.: Okay. Jennifer?

Jennifer: Um, I have an example that might work. Um, like when you make cookies. You have all your different kinds of ingredients, and you don't know what your cookies are going to taste like. So you're mixing them all together, and then you're just going to see what it tastes like.

Matthew: Like what we did with that cake in Science Challenge. That was wicked. You just took everything, as much as you wanted. And that one time me and Chad, we took too much baking soda, so we had to run to the sink, and it overflowed.

Ms. S.: [laughing] I think I remember that. Jordan, you had something a minute ago.

Jordan: That Frank's was too salty.

Ms. S.: Okay. So, yeah, all of those things are pieces of chemistry. And today I'm going to see what you guys have to say. When we study chemistry, we often are trying to find out, also, what is all this stuff made of. Like, what's actually happening when all of that goes on? So what happens when you mix vinegar and baking soda? Like, what is that? Jennifer?

Jennifer: A chemical reaction.

Ms. S.: Okay. But what happens? If you had those super-magnifier eyes, what would happen? Matthew?

Matthew: Maybe you would see these different reactions going into, like, the vinegar going into the baking soda. And it's sort of like mixing and surrounding. And then it gets too big, like the one we did with the bottle and the cork. We poured vinegar in there and the baking soda, and then we put the cork on and we went outside, and then the cork flew far, because of all the pressure the baking soda and vinegar's making.

Ms. S.: And so what do you think is happening there? Why does that happen?

Matthew: Um, I don't know.

Ms. S.: Robert?

Robert: Maybe because the vinegar is all one thing, and then the baking soda's one thing, and when they meet they don't like each other almost. So then they -

Keith: It's like the baking powder is a bacteria and vinegar is the medicine to kill it. So they're fighting, and it's a big battle.

Robert: Yeah.

Ms. S.: Okay. Samantha?

Samantha: Or else, it's something like Keith and Robert's, except the opposite. Sort of like the vinegar is one thing, and the baking soda is another, and when they meet, they create a whole new thing. Like, 'cause when you have the vinegar and you put it into the baking soda, they create fizz.

Ms. S.: All right. Rachel?

Rachel: Um, kind of like another example is two big men or whatever, and they don't like each other, and they start a fight. And then something happens and stuff. (Class Discussion, March 25)

The importance of unpacking vague abstractions such as "chemical reaction" is elaborated upon in Section 4.3.2.2.4, where using poorly understood abstractions is presented as a Level 2 AR strategy that fails to establish the validity of a source analog prior to using it as a source of explanatory structure.

Once the importance of broad parameters for defining analogy as it pertains to this study has been established, another question assumes prominence: How do students generate analogies and subsequently identify whether the transfer of explanatory structure from these analogs to unfamiliar situations is justified? The answer to this question lies in the developmental framework that is presented in the remainder of the discussion of analogical reasoning.

The ability to generate analogies does not appear to be something that can be readily learned or practiced. Analogy is simply the way the mind works. I define analogy as "a perceived relation between two objects, situations, or processes that differ in one or more ways and between which explanatory structures are transferred." By this definition, virtually everything that our minds perceive is the result of a connection with prior experience or thoughts about experience. This forms the basis of the observational dependence of theory and for a constructivist theory of learning. Taking this proposition to its logical lower limits, it also presupposes certain innate ontological categories of the sort proposed by Carey (1995, 1996) and Carey and Spelke (1994). The human mind can generate an analogy far faster than we can direct it to find one, and analogy guides our thinking in ways of which we are not consciously aware. So saying, however, I do suggest that analogical reasoning is something over which we may exercise more conscious control. I propose two important ways that I believe it can be more effectively channeled to make more effective use of its power and to avoid its trappings. The first involves the recognition of both the value of the ideas that seem to come naturally to mind and of the limitations that these may impose if we are not aware of the manner in which they direct the way that we think. It is this belief that frames the developmental AR categories presented here. The second is more speculative and deals with the creation of knowledge structures that better facilitate the connection of information within our minds. I believe that this indirect approach is the only way that new analogical possibilities are actually created. The integrated knowledge base that seems to be at the root of many effective analogies may be rooted in a habit of mind that continually asks, "Why?", remains focused on increasing depths of explanation long enough to create a dense web of connections between related ideas, and reduces ideas to levels that allow easy transfer to other domains. These ideas are discussed in greater detail in Appendix I.1.

When developing analogy-based explanations, students begin with a general analog structure and attempt to determine how various identified components are related or mapped within that structure. As in the FOI progression, higher levels of AR show increased awareness of the need to evaluate the applicability of suggested ideas, but understanding of the process of reasoning by analogy impacts students' AR development in ways that go beyond FOI levels. At Level 1 AR, analogy is used as a communication tool whereby the student describes new situations by reference to other more familiar situations. Explanatory transfer takes place at an implicit level. The role of implicit mental models is discussed in this context. At Level 2 AR, the thinker is explicitly aware of the role of analogy in formulating explanations, but explains away negative components of selected analogies with the rationale that they are "just analogies." Students at this level realize that it is unnecessary for all components of identified analogs to correspond, but have not clarified this understanding to the point of realization that such correspondence is necessary for those elements upon which explanatory structure depends. "If *x* can do it, so can *y*" seems to characterize the form of reasoning that underlies Level 2 AR. A common observable indicator of this belief may be seen in statements such as: "It acts like *x* (a living thing), but it's not really alive." If the target analog is not considered alive, an animistic rationale for its behavior is no longer plausible. In other words, students may recognize that it is inappropriate to personify non-animate objects and claim not to be doing so, but devise explanations with rationales that are wholly dependent on animist intent. By Level 3 AR, students are aware of the need to evaluate carefully the applicability of selected analogs in new situations. To value and evaluate seem to be the keys to analogical reasoning at this level. As one of my students explained, just because you can relate them doesn't mean the analogy makes sense. In keeping with the format used to describe Level 2 AR, this could also be expressed as, "Just because *x* can do it doesn't automatically guarantee that *y* can, too." There is some evidence that using animism as a context for reflection on the transferability of explanatory structure may be effective in catalyzing the transition to Level 3 AR. As a result, animism is treated as a separate case at the end of this section. By Level 4 AR, a thinker must demonstrate awareness of previously unconscious constraints on the idea-generation process and make conscious attempts to break free from these bindings. It is possible that recognition of the role of reduction (discussed in Appendix I.1) may also prompt conscious attempts to build integrated knowledge structures that are based upon effective reductions, but this was not observed in either the students in this study or in the experts considered in other studies.

If the levels of idea-generation outlined here are in fact developmental levels, the oft-expressed concerns about the limiting effects of students' unarticulated and vague conceptions on constructivist approaches to teaching and learning (Gunstone, 1994; Nersessian, 1992b; Strike & Posner, 1992; Vosniadou, 1994; White, 1994) are not only unfounded, but also stand in stark contrast to the very process of knowledge construction. Learning to articulate and evaluate vague ideas is critical to learning, not something that should be bypassed for fear that the students will do so incorrectly.

#### 4.3.2.1. Level 1: Implicit explanatory transfer.

At Level 1 AR, there is some evidence that very young children make use of analogy as a communicative strategy. In so doing, they must articulate the metaphors upon which their ideas are based, but likely do not realize that they are doing so. The transfer of explanatory structure by analogy is entirely implicit. Thought is centered on action and direct representation of action, and action may be rooted in implicit analogical reasoning. This idea is based upon both the Piagetian schemes described by Duckworth (1996) and the notion of elemental physical intuitions described by Clement (1994).

Vosniadou (1987) cited evidence from several studies supporting the conclusion that "children produce metaphor-like utterances as soon as they start talking, and are capable of understanding simple metaphorical expressions by the age of 4" (p. 870). At this level, students are likely unaware of the metaphorical construct, but simply use it as a communicative aid. By Level 2 AR, recognition of analogy as such allows for its conscious use as a communicative strategy. It is also consciously used as a source of explanatory structure, but lack of metacognitive understanding of the process of explanatory transfer precludes effective evaluation of the applicability of the analog relationship.

Duckworth (1996) described the importance of generalized schemes that may drive action:

> What each of them [insights about the way objects react] represents is what Piaget calls a "scheme." The totality of your schemes is the totality of what you know. At the pre-language, symbolic level, your schemes are what you know how to do. (p. 19)

She emphasized that "It is important to realize that what is known, a scheme is more general than any one instance of carrying it out" (p. 19) and related the development of a motor scheme to the manner in which children generalize rules of grammar when they are learning to speak. This generalized action-knowledge may lie at the heart of Level I approaches to scientific activity and likely forms the basis for idea-generation at all subsequent levels.

Duckworth's emphasis on physical knowledge and the generality of the schemes that she proposed are further supported by Clement's (1994) discussion of elemental physical intuition, which he described as "knowledge structures that reside in long-term memory and can be activated to provide an interpretation or an expectation about a physical phenomenon" (p. 212). Clement developed this concept as a result of watching and listening to expert problem solvers (advanced doctoral students or professors in technical fields) as they worked through the wide-vs.-narrow-spring problem discussed in Chapter Two (to determine and explain which spring would stretch further with equal weight attached). I am not suggesting that his subjects operate at Level 1 AR. In reading the transcriptions of their approaches, it is clear that they progress far beyond their initial intuitions as they identify and evaluate their intuitions. Nevertheless, the initial vague sense that they describe may be very similar to the thinking of young children. The difference is that young children do not recognize or reify their intuitions. According to Clement, observable behaviors that often indicate the use of physical intuition include:

1. "intuition reports" (p. 211): The subject states that he or she is making a prediction based on an intuition.
2. unjustified statements: A physical intuition is something that the subject does not question; it is something that he or she thinks with rather than thinks about
3. statements that refer to situations that are "more general than the memory of a specific incident" (p. 211), "do not refer to a specific episode in the past" (p. 221), and prompt "an expectation for what will happen over a wide range of circumstances" (p. 221)
4. self-evaluation of plausibility: Confidence in a prediction is based on internal criteria rather than external authority.
5. orientation to concrete objects: "Subjects usually speak of an intuition as referring directly to objects and physical phenomena, not to abstract equations." (p. 211)

Later, he discussed the role that "spontaneous imagery reports" (p. 215) play in elemental physical intuitions:

> To anticipate, the view that I propose here is that although imagery plays a role in physical intuition, elemental physical intuitions do not just consist of specific images. Rather, they involve a general schema, often an action-oriented, perceptual motor schema accompanied by kinesthetic as well as visual imagery. (p. 213)

Although the analogies generated by the students in this study were primarily action-oriented, it is possible that the general to specific pattern noted here may also be a significant indicator for identifying instances of mental models which are not immediately rooted in physical sensation. As a result, I prefer a more general reference to implicit mental models. Semantics aside, however, the main point of importance is recognition that implicit analogs often drive expectation, action, and perception in a manner of which we are not consciously aware.

In the following example, Robert's intuitive confidence in his idea, its apparent generality, and his obvious association with concrete objects (as evidenced by his gestures) would likely qualify his thinking at this point as an example of an implicit mental model (which, in this case, is likely also an elemental physical intuition):

| | |
|---|---|
| Robert: | And to get a hot wire, then your energy would mix together, and then it would [motioning] try to, like, on a plus and a minus, on the, pretty much on the plus and minus side of a battery, er, of a magnet. They would push each other back [motioning with his hands]. |
| Ms. S.: | So, one side is a positive, and one side is a negative, so when they come together.... |
| Robert: | Then they...like...shake. Almost. Yeah. Pretty sure. And the reason it doesn't do that in the bulb is because it's separated from.... It never has to meet. (Battery Interview, March 26) |

In the following case, he did not even attempt to justify why the electricity would need to flow through both wires:

| | |
|---|---|
| Robert: | Yeah, because it knows, or.... It doesn't know, but it can.... It has another connection on to it, so then it has to send something down there. And then in your other bulb [drawing a diagram].... And you've got.... This is your plus, right [drawing a diagram]..., and then this is there, |

> 'cause you've got it going like this. (Battery Interview, March 26)

Implicit, generalized knowledge may also be at the root of an outwardly animist explanation that Robert expressed during his battery interview:

> Robert: Well, it would be in this one too, but it would be like up here, so that only certain kinds could get through. So, in this one, there would be good energy going in, and there would be dividers on both sides, and then it would go through here, the good stuff, and then it would go in here, and this divider would be open, and this right here would also be open.
>
> Ms. S.: For good stuff and bad stuff?
>
> Robert: Just for the bad stuff. This one opens, and then this one also opens. Because it knows that this bulb has gotten the stuff it needs.
>
> Ms. S.: How does it know?
>
> Robert: Because it's lighted.
>
> Ms. S.: So it sees the light?
>
> Robert: Like inside here. The little wire is hot, and then it goes down through here and then here. The divider there blocks it, so this one knows the energy coming through it has to let some by to get into this one. So it won't back up into this one...so the bad energy can go back into the bad cell.
>
> Ms. S.: I'm still not sure how it would know.
>
> Robert: [thinking and drawing] One atom would be coming into here and over to this side, and then here it would go up here, and then you've got your divider here, and then the energy here is active. It's, like, moving because it's good, and this is being forced open, and then this one knows that there's good energy from here, because this one got moved, so it comes in, and then it lights here. Then this one over here, it has its divider, and it goes from here to here, and it can't get in. It just waits till there's good energy to move and be active, so it will open it.

Ms. S.: So, only good energy can open it?

Robert: Yeah. Good energy is the key to open it.

Ms. S.: So, how come bad energy opened this one?

Robert: Well, this one, the good energy opened it, and then this one opened also.

Ms. S.: They opened at the same time?

Robert: Yeah, because one of them got good energy. Just in case you ended up with good energy from this side. Like, if your bulb was put in another way.... (Battery Interview, March 26)

Robert was typically very adamant about refuting animism, so it does not seem viable to attribute his explanation to it. However, describing mechanistic chains of events without explaining the causal mechanism that drives those chains could very well be part of a general implicit mental model based on devices that perform a series of operations sequentially: That is just how machines work.

Frank struggled throughout his interview to identify the nature of the scanner he discussed in the following segment. During this discussion, he moved from an apparently animistic explanation, although he seemed quite certain that the particles were not really alive, to a vague explanation that invoked magnetic force as a causal mechanism. It was not until much later in the interview that he articulated his magnet idea more clearly. It is possible that this was an implicit notion in his mind all along. Frank's ongoing consideration of the issue, at least partially in response to a lengthy series of probing questions, eventually led him to a more explicit description of what might have been happening in the battery and wires of his circuit:

Frank: So, like, when you hook it up it still will work [reversing the alleged positive and negative wires and reconnecting the circuit]. See, it still works. I think that once you hook it up, it quickly just scans through, and if it's not the right one, it'll quickly change it to negative if it's not negative. Because the shocks come from the negative end. So the shocks will shock it, and it'll change it if it's not negative. So, like, if this one was negative and not positive, it would scan through there and change it.

Ms. S.: Do you have any questions about that?

Frank: No.

Ms. S.: Well, I'm wondering how it would happen. How does it suddenly just change things from negative to positive?

Frank: Well, the shocks just.... It'll come through here, and it's sort of like a scanner. So like, it'll scan through here, so it's sort of like a person who's gassing something. So it's like some gas that shocks up some acid, some of the same energy. It'll go and scan through, but it'll stay, right. So once it gets to this end, it'll sort of just butt in right in front of the first one, and then will get let out, but then he'll come back once that first guy is used. So, he'll go around making sure everything is positive and everything.

Ms. S.: So, how does he make it positive if it's negative?

Frank: Well...because.... Okay, sort of like this. They all hook on, right. And once he finds one -

Ms. S.: And what is this "he"?

Frank: Well, the marble.

Ms. S.: So, it's a new marble?

Frank: Well, yeah, it's a new marble, and he comes and he's scanning everything -

Ms. S.: How does it scan? What do you mean by, "It scans"?

Frank: Well, not the same, right? So he looks for the ones that aren't the same, because -

Ms. S.: But how does he look? Like, is it alive and has eyes?

Frank: No.

Ms. S.: How does this new marble know when one of them is different?

Frank: Well, um....

Ms. S.: Tough one?

Frank: Yeah.

Ms. S.: Can you tell me what you're thinking as you sit there, and just talk out loud.

Frank: I'm just thinking how could it -

Ms. S.: And how are you trying to figure it out?

Frank: Just thinking of ways, like smells, or also of different ways. Maybe it's a different kind of energy, because it's a different kind of acid, right?

Ms. S.: Different from what?

Frank: 'Cause it's different from.... It's a different kind of energy, right?

Ms. S.: What's a different kind of energy, though?

Frank: The stuff that came out of this one [pointing to wire].

Ms. S.: Okay.

Frank: Right?

Ms. S.: Uh huh.

Frank: Well, the positive stuff, right? So the stuff that comes out of the positive is, uh.... We should be talking about the negative. So the stuff that comes out of the negative is different from the stuff that's positive.

Ms. S.: Uh huh.

Frank: And maybe it has, um.... Maybe it has, sort of like.... Maybe it's a magnet, sort of like. Magnetized, right?

Ms. S.: And where's the magnet?

Frank: Oh! Okay, I've got it now. Like the whole energy piece, right? The particles of the energy is magnetized. And what makes them explode in the light bulb is from the magnets. The two different kinds of energy. So if you have a magnet here and a magnet here, and they're both the same side, and they suck in, right? And if you have one here, and you flip one around, they won't go, right?

Some time later, he finally made the scanner idea even more explicit:

Frank: Um, 'cause now it makes more sense. 'Cause if you come right here, there would be from the shocks, right? And then since there's.... Since this one's a different kind, it would be pushing away, so when it comes, it'll -

Ms. S.: So the shocks convert it back to negative?

Frank: Yeah. See it feels like that. It actually goes like that when it's a magnet. When you go on top, like this, it goes like that, and it pushes it this way [imitating magnetic attraction and repulsion with his hands]. Like it pushes it away from the side of the magnet. (Battery Interview, March 16)

At this point, a kinesthetic sense was clearly influencing Frank's thinking. As with Clement's (1994) experts, Robert's and Frank's ability to verbalize and evaluate their intuitions indicates transition to at least Level 2 AR, but the examples provided are useful in illustrating the nature of what were clearly implicit ideas prior to their describing them during their interviews. It seems that the need to describe ideas to others is a powerful stimulus in the identification of descriptive analogies. When evaluated at Level 2 or Level 3 AR, descriptions such as these become even very useful in generating meaningful explanations.

#### 4.3.2.2. Level 2: Assumed equivalence: "It's just an analogy."

Many of the students observed during this study made extensive and deliberate use of analogy, both as a means of communicating visual images and for suggesting causal mechanisms operating within the phenomena they were attempting to explain. In so doing, they often mapped similarities between a source and target analog, but typically displayed little conscious effort to determine why the relationship should apply in both instances or regarding what limitations should be placed upon it. When analogs are challenged, students at this level are likely to explain away discrepancy with, "It's just an analogy" even if the part being challenged is the part upon which their explanation resides. This is likely partially related to the Level 2 FOI difficulty in understanding what is meant by "How…?" and "Why…?", but even students at Level 3 FOI do not always evaluate the validity of proposed analogs. This suggests that understanding the nature of analogical reasoning is dependent upon unique elements that are separate from FOI criteria. Conscious evaluation of analogy commonly centered on understanding of the source analog rather than the transferability of explanatory structure from the source to the target. Invented analogies, or generative transformations, are typically modifications to proposed analogs generated in response to difficulties with those analogs. At Level 2 AR, these inventions clearly reflect the evaluative techniques typically used at this level. They focus primarily on the creation of visual images consistent with observed phenomena and typically do not involve consideration of whether the causal mechanisms underlying apparent similarities are transferable. "If a magnet can do it, so can an atom" is the type of reasoning that seems to underlie thought at this level. This may be contrasted with the invented bridging analogies that are evident in the expert strategies described at Level 3 AR. Finally, the use of proxy abstractions by students at this level further illustrates their lack of a perceived need to rationalize the transfer of explanatory structure.

#### 4.3.2.2.1. Conscious use of analogy.

By Level 2 AR, students explicitly recognize the value of analogy in communicating ideas. In the following examples, Rachel's suggestion for the "Things that Helped" list appears to focus on the power of analogy to help paint a clear visual image. Carl's match-head analogy was intended as an explanatory framework, but consideration of whether the causal relations acting between the components of the match-head corresponded to those operating in the battery was not undertaken by either Samantha or Carl. The perceived similarity in structure between the match-head and the battery was used as prima facie evidence for the applicability of transferring explanatory relations between them. However, Samantha's ability to identify the use of analogy as a strategy provides evidence of her explicit understanding of the analogical construct:

| | |
|---|---|
| Rachel: | Um, examples help a lot. |
| Ms. S.: | Okay. Like, what do you mean by an example? Can you think of one? |
| Rachel: | Um, like, some people had two-way traffic and stuff. Like, an example of that is on the road there's two ways. |
| Ms. S.: | Okay. |
| Rachel: | And they go up and down or whatever. They help some understand it a bit more. |
| Ms. S.: | So you like the two-way traffic one. Okay. Any other of those? |
| Samantha: | The fire one. Like the friction. How to light a match, and you have to use friction to light a match. It sort of had to do with friction needed to make shocks or something. |
| Ms. S.: | All right. |

| | |
|---|---|
| Carl: | You had to have both. You can't have one without the other. |
| Ms. S.: | So you like using.... You like it when people use those? |
| Samantha: | Yeah. (Class Discussion, March 16) |

The following day, Andrea made a comment similar to Rachel's, once again highlighting the effectiveness of analogy in painting a clear visual image:

| | |
|---|---|
| Andrea: | And I have another for "Help." I don't think it's on here. Um, I think it was Samantha. She uses a lot of, like, examples, like in real life. Like, highways and stuff, and it helps me picture it in my head. Like in an actual wire or whatever. So, examples or - |
| Ms. S.: | Can you give an example of an example? |
| Andrea: | Someone said that there're tubes in Frank's that follow a track or whatever. Or train tracks. And then someone said to picture train tracks, and so I did, in an actual wire, so it helps. (Class Discussion, March 24) |

The following excerpt from Keith's journal reflects his awareness of the use of analogy, but demonstrates no evidence of an attempt to determine if motorboats are an effective way to describe the movement of energy through wires. The motorboat analogy may simply have been a way to communicate the visual image that he saw in his mind when he tried to envision the operation of his battery:

> How I think a battery works is the electrical peices are everywhere. The nail on the negitive side of the battery is toching the Energy wich I think is like motorboats driving on hot water they go along the wire they don't need to be steered they just motors along the wire when they get to the light bulb the areia to get through with so many other electrical peices is so small that when it trys to get through it causes friction wich is so much that it glows and make the bulb light depending on wich side the electric peice came from + or -. The motor boats are just an analogy! The positive side a c-cell has a thing to build up Enargy so + has more enargy than the negative side of the

> battery. A dead battary is all the Enargy with burnt out. (Journal, March 9)

Although students at Level 2 AR explicitly recognize analogy as a communicative strategy, they do not consider the applicability of analogical relationships. This is true even when the analogs are clearly intended to define explanatory mechanisms. For example, as he was explaining his view of the particles of baking soda and vinegar, Frank made the following comment: "And if it's plus and minus, they'd attract just like a battery" (Chemistry Interview, June 5). In this case, Frank transferred causal explanatory structure from his understanding of a battery (for which the explanatory structure came from magnets) to his understanding of the forces between atoms. He did not consider why the same forces might act in both cases, and simply noted similarity between the two situations without questioning the validity of the relationship.

Once students realize the value of analogy in describing their ideas, they sometimes deliberately seek appropriate analogies to help them do so. The reification of vague intuitions that come to mind appears to be an effective source of analogs and was used both by Clement's (1994) experts and the students in this study. One of Clement's subjects used a strategy whereby he selected a feature he deemed salient to the phenomenon he was considering and used it to search for other analogs. He noted: "I'm imagining holding something that has a certain twistyness to it and twisting it" (p. 214). Clement used this statement to explain the role of perceptual motor schemas in physical intuition: "I assume that perceptual motor schemas for twisting and bending objects were built up from the subject's prior experiences in acting on many concrete objects" (p. 222).

Clement also noted that the presence of non-verbal schemas created a need for an "auxiliary description process" (p. 215) if the subject was to describe his or her thinking. These descriptions appear to rely heavily on analogy, and may hold promise for helping students to identify their own implicit mental models. As Rachel was describing her theory of vinegar and baking soda, she started off with a rather general sense of how she thought the reaction was proceeding. To better explain what she was trying to say, she turned to specific examples:

> The vinegar and baking soda crashes and makes bubles. The bubbles are filled with air, so it grows. When the bubbles pop, the vinegar and baking soda get smaller. Example: When you swallow air, you burp. Sometimes when you eat you feel full then when you burp, you have more room. When you are swimming, the water is moving and air gets trapped in the water. The atoms attract and hit each other, because they are oposite. The gas stays in there. The bubbles are poping. Eventually the gas leaks out. (Journal Entry, April 22)

Although it cannot be assumed from reading her journal that she generated the general statement first, if she did, the need to explain it may have been what led her to identify more specific instances that were rooted in a physical intuition. The generality of the first statement is consistent with Clement's (1994) description of physical intuition. Both the burp analogy and the bubbles-in-the-water analogy could have been rooted in direct physical experience, although the two seem to focus on quite different physical-kinesthetic sensations. As this was a journal entry, it is unclear whether other indicators were also present.

As students become increasingly familiar with the analogs that guide their thought, and as they explore these at more explicit and deeper levels of understanding, it seems plausible that they could develop a wider repertoire of articulated abstracted thought patterns to think with in a variety of situations. It would be interesting to monitor their continued use of analogy over a more extended time period to see if certain broad-scale analogs recur in different contexts. Although the nature of magnetic force was never carefully considered, it formed a recurring theme for some of the students as a means of explaining the movement of particles and / or energy through the wire in a circuit and of describing the nature of the attraction and repulsion between particles of matter during a chemical reaction. If the students do continue to use and build upon the analogies that they articulate and map, this could implicate the importance of helping them to develop their own analogies as a method of generating more integrated and widely applicable knowledge bases.

#### 4.3.2.2.2. Confirming understanding of the source analog.

> *Unlike the empirical law, the model [billiard ball model for the empirical gas law] provides a description of a hidden process that explains how the gas works and answers "why" questions about where observable changes in temperature and pressure come from. Causal relationships are often central in such models. The model can not only add significant explanatory power to one's knowledge but can also suggest questions that stimulate the future growth of the theory.*
>
> (Clement, 1989b, p. 346)

Willingness to question understanding of a source analog appears to precede an understanding of the need to consider the applicability of the analogical relationship itself, and typically occurs during the mapping process. The students in this study commonly questioned each other regarding their understanding of the phenomena upon which they based analog relationships.

In the following dialogue, Carl's match-head analogy binds the target to the source only in his recognition that both situations require two components to make energy. The applicability of this relationship was not considered. However, a rather lengthy argument that challenged his understanding of the source analog did develop. Several members of the class were unwilling to accept friction as essential to fire, and thereby refuted Carl's analogy on this premise. Although the relationship has plenty of potential at a deeper level in that both fire and batteries rely on chemical reactions, the students were unfamiliar with the nature of the chemical reaction that produces fire. At this point, perhaps I should have provided this information to them. It would have been immediately useful to them in their evaluation of the salience of friction, and it seems likely that the notion of friction would have easily given way to the more general concept of kindling point. This may have helped the students refocus on the notion that fire indeed requires two material things, but that these are fuel and oxygen. In turn, this may have diverted the discussion along a more productive route:

Keith: What happens if you try to light a bulb from the same side [two wires connected to the same terminal of the battery]. It will [should] work. How come?

Carl: It doesn't work, because it needs both sides to explode.

Jordan: So, okay, is there two different kinds of energy?

Frank: Yeah!

Carl: It's like a match and a match-head. You can't keep a match going without the match-head. Like a light bulb. You can't keep a fire going without fuel.

Frank: So the new energy comes and covers for it. And that'll go back in and it'll keep on.

Robert: Yeah.

Carl: And then, like, same thing with a bulb, though. Have you ever tried to light a match by friction? You just strike it and it's lit, right? Have you ever tried lighting it without friction? Try blowing on it until it lights next time. It doesn't work too good.

Andrea: It works if you strike it on your jeans.

Carl: Yes, I know that. But see, you can't light a match without friction. Just like you can't light a bulb without both types of energy.

Robert: You can light a fire without sulfur.

Jordan: Yeah. You can light a fire with just a stick and a little groovin' thing.

Carl: It's friction!

Jordan: Or you can go like that [rubbing hands together].

Carl: It's friction! It's all friction! You can't light a fire without friction. Unless of course it's lightning, but that's friction, too.

Jordan: So, okay, if there's a fire on the water once, what -

Carl: There was fire on the water?

Jordan: Yeah.

Carl: Because somebody poured gas on the water.

Frank: Or oil.

Carl: Or oil.

Jordan: Well if you went up to a slough with a whole bunch of oil and threw a match in it, it would start on fire?

[Here, Jordan seems to be alluding to the fact that not all heat sources originate with friction. He has been able to generate one specific example in his attempt to communicate his idea, but his point is not clear to everyone. I should have been more alert to this and helped him to move past his oil-on-the-water example to other instances where heat is generated without friction; e.g. sunlight through a magnifying glass]

Carl: Yes. But you had to light the match first, didn't ya? You had to light the match with friction didn't ya?

Ms. S.: Okay. And what is the friction to do with the battery now?

Carl: The bulb is like the match. You can't light a match without friction, and you can't light a bulb without both kinds of energy.

Jordan: But still, what if everything falls to the bottom of the water? You'd have to dunk the match down into the water -

Frank: No, 'cause oil floats.

Carl: Oil floats on top of water.

Samantha: So does gas.

Jennifer: Haven't you ever seen *Free Willy 2*?

Samantha: The oil sits on top of the water, and then something happens.

Jennifer: And then their ship exploded, and then everything else started on fire.

Jordan: So, movies aren't always real.

Carl: That is real.

Robert: If oil lights like -

Carl: Just certain types of oil. Like cooking oil does.

Class: [arguing about whether oil is flammable]

Ms. S.: Okay, guys. I'm wondering if this is getting.... Is this helpful in understanding the battery? If it is, say so.

Carl: Jordan's wondering about how you light the bulb.

Ms. S.: Okay.

Carl: You can't light a match without friction, and you can't light a bulb without both kinds of energy.

Frank: Yeah. (Class Discussion, March 11)

At this point, the entire argument was centered on whether all fire is caused by friction. During his individual chemistry interview, Carl again used fire as a source analog in an attempt to understand the vinegar and baking soda reaction. This time, he did consider the role of oxygen:

Carl: Well, this is acid, so maybe oxygen is kind of fuelling the fire, 'cause oxygens are fuelling the fire. What comes out of fire?

Ms. S.: Carbon dioxide.

Carl: Oh, cool. That supports that theory also, 'cause I know that that's what comes out of it [the vinegar and baking soda reaction], too. 'Cause that's what comes out of this mixture. So, if some of the extra O's are fuelling the fire, then out comes $CO_2$ gas.

Ms. S.: If it's the same type of burning.

Carl: Yes, if it is the same type of burning. I doubt it, because there is no heat involved. (Chemistry Interview, May 25)

Carl's considerations of whether the two situations represented the same type of burning is indicative of transition to Level 3 AR, although it was instigated by my challenge of his assumption and does not reflect a generalized understanding of the need to consider the applicability of analogy. In this case, the identification of heat as a salient difference between the two situations may have actually directed him away from a useful analogy that focused on the more general nature of a chemical reaction rather than on the specific nature of burning. However, arriving at the right answer for the wrong reason (i.e. due to an unchallenged assumption) is no more acceptable in a line of logic to evaluate a scientific theory than it would be in a math problem where two calculation errors cancelled each other out to produce a correct answer. In the next section, I focus specifically on the manner in which descriptive analogs are used with little consideration of their applicability.

#### 4.3.2.2.3. If *x* can do it, so can *y*.

All of the students generated analogies to help them explain their ideas. In this section, I present a collection of analogies generated by Carl and Samantha. I selected their work because they made extensive use of highly descriptive analogs. Despite this, evidence of spontaneous attempts to evaluate the validity of their analogs is very sparse. They seemed to assume the equivalence of source and target analogs on the basis of outwardly similar behavior that contributed to consistent visual images. So long as the analogs could be used to generate images that could explain observed phenomena, the means by which they did so did not concern either of these students. Furthermore, there were several instances in which analogs were modified to better describe the situations being explained. This indicates that they were actively evaluating their analogs, but not in terms of transferable explanatory structure. If the students could be made more aware of the importance of evaluative strategies that go beyond description, their ability to generate scientific explanations would likely improve.

Each of the examples is annotated with questions that could have been used by the students to deepen their understandings of the phenomena being explained. The questions are intended as examples of ways in which more careful evaluation of the validity of the analogical relation could have led to further development of the proposed ideas. At first, questions such as these may need to be provided by the teacher (or by peers capable of providing these sorts of challenges). Through reflection on the resulting expansion of their ideas, the students could likely learn to recognize the value of this strategy and to then use it more independently.

It should be noted that there may be times when it is prudent to accept analogs for the time being unless a blatant reason for not equating a source and target is apparent. Otherwise, it seems likely that one could become mired in the details of isolated components of an explanation and lose sight of the broader explanation. Eventually, however, the validity of all analogs needs to be considered.

The analogies presented in this section were generated by Carl during his battery interview. With the exception of examples 3, 6, and 13, all of these assumed the transferability of some component of the source to the target analog. The three exceptions are inventions generated as a means of making the behavior of the source analog consistent with the behavior of the target.

1. **The water tub.** (Can charge be poured like liquid?)

| | |
|---|---|
| Carl: | But this is kind of like the same kind of energy, so I might do this instead. Like, put it out through here, and then it gets charged again, maybe. |
| Ms. S.: | So as it comes back in, it's still good, and it's reused, you mean? |
| Carl: | No, not still good, but it's old, and then it sort of gains a charge from the other ones. |
| Ms. S.: | Okay. |
| Carl: | Like, if you have three tubs of water. One's – two tubs of water – and one's all the way full and one's empty, and you want two pails of water, what do you do? You empty half of the pail into the one, |

empty one. So maybe each of these little ones in here puts a little bit into the other one.

2. **The one-way street.** (Traffic is controlled by willful drivers. What directs the traffic in a wire?)

Carl: I want to have it rechargeable. And so once this is all dead, maybe, um, a charger, a battery charger, draws all the old energy out of here, out of this way, and puts new stuff in here. This is the charger now, so it puts new energy in here, releasing into here because this is a one way street. And this is a one way street.

In the next example, Carl started with an analogy that I suggested and modified it in a manner that made it accountable for the friction he needed for his explanation:

3. **Rough-marble energy.** (What is going through the wires?)

Ms. S.: All right. And so what is it that's causing these bulbs to light?

Carl: Friction. Like, inside here, the little wire, it maybe squeezes. The inside edges are rough or whatever where it travels through. And it's smaller, so it squeezes, and it causes more friction for it to get through.

Ms. S.: For what to get through?

Carl: The energy.

Ms. S.: So, is the energy a thing then?

Carl: Could be. I'm not exactly sure. It's what I think.

Ms. S.: Yes, I know. But try to evaluate what you think.

Carl: Well, when it goes through the light, it's rubbing against the edges of the wire or whatever.

Ms. S.: Okay.

Carl: And it's going really, really fast, so it starts to heat it up. And then you get light! 'Cause it's heating up red hot.

Ms. S.: So what is it that's hitting?

Carl: It's maybe rubbing against the sides.

Ms. S.: But what is rubbing against the sides?

Carl: The energy.

Ms. S.: Which is?

Carl: Energy. It's kind of hard to explain. Energy can only be one thing. It can only be energy.

Ms. S.: Yes, but I don't know what you mean by energy. Could you explain it?

Carl: Um.

Ms. S.: Like, if it's creating friction, is it a thing? Do you like the marble thing? Or do you have a better way of....

Carl: Yeah, marbles. Chip marbles. Rough marbles.

Ms. S.: Okay.

Carl: And they're being pushed, they're not rolling.

4. **Laser beam in a mirrored room.** (Do these beams keep going indefinitely until the hole is opened? What in a battery might behave like a laser? Why?)

Ms. S.: And what's pushing them?

Carl: Um, maybe the energy is compressed in there a little bit. Not much, but a little bit. And so when it gets connected to a wire, it just shoots out, 'cause it's being.... It wants to get out. It's like if you put a laser beam...shoot a laser beam into a mirrored room, and then you close off the hole that you shut it in, what's going to happen to the laser beam? It's gonna go everywhere. And then once you open up a small hole somewhere, it's eventually going to hit that hole and go out.

In the following situation, Carl's identification of the gate as "just an analogy" is typical of the metacognitive understanding that drives the level of analogical reasoning in which he is engaging. At this level, negative components are not viewed as a concern, because analogical situations are recognized as similar, not identical. However, students at Level 2 AR have not learned to discriminate between which parts do need to correspond and which can be reasonably ignored as non-corresponding elements of the analogs.

5. **Conducting gate.** (What part of a wire could act as a gate?)

Carl: Um, like a gate. Something that doesn't conduct electricity is like a closed gate with a bunch of people around it. Like a big iron gate thing that reaches to the ceiling or something. If there's people pushing against the gate, it's not going to open. But if it's an open gate, they can just go through. So wires can open the gate. This is an open gate until it reaches about here. Then it has nowhere to go.

Ms. S.: So, is it an actual gate? Is there actual tiny gates in the wire?

Carl: Well, that was just an analogy. I don't think so, but it would be cool. You could look at it through a microscope or something.

Ms. S.: What do you think you'd see?

Carl: Little bitty gates. A bunch of people crowded around it. Well, if there was a gate in there, I'd probably see a small, itty-bitty, tiny little gate that only covers the end of the wire. And then if you hooked a battery up to it, if it was still a closed gate, energy would be pushing against the gate, but it couldn't go anywhere. That's about it.

In the following example, it appears that Carl did consider the transferability of explanatory structure between a toaster and a light bulb. Initially, he simply identified a toaster as like a light bulb in that both are composed of short circuits, but it appears that he may have questioned this relationship with, "Then why doesn't the toaster light?" This could have prompted the invention of the airtight, "juiced-up" toaster. This is a good example of the Level 3 AR strategy of bridging, which is described in Section 4.3.2.3.

6. **Toaster light bulb.** (clearly mapped and altered to suit purpose)

   Ms. S.: So, what happens when it gets to the light bulb?

   Carl: The light bulb causes friction because of the small wire. So when the marbles go past it, it kind of rubs the edges of the marbles, and it causes friction, causing it to heat up, and it makes it glow red. Bright red. Like if you could juice up a toaster so it would take enough power in, you could probably get it to glow like a light bulb. Except that it would spark and then it would short out because it has air.

   Ms. S.: What has air?

   Carl: The toaster. If you could seal up a toaster, and juice it up so it would take enough volts or amps or whatever, you could get it to glow like a light bulb. And that's about it.

7. **Fire.** (In what way do the components interact to produce fire? How could this relate to the battery?)

   Carl: Well, I can think of something that needs three to work.

   Ms. S.: What's that?

   Carl: Fire. You need oxygen, fuel, and heat to start a fire. If you don't have heat, you don't have a fire. If you don't have fuel, the fire will go out, and if you don't have oxygen, it won't even start. So.... This is confusing.

Ms. S.: So, on the oxygen, fire, heat thing, why do you need all three?

Carl: Well, fuel is something that will burn, so once you have a fire started, you need fuel to keep it going, and you need heat to start the fire. Friction. You need oxygen, 'cause the fuel burns oxygen. The fire will burn oxygen when it's going. And I don't know why it needs all three.

Later, during the chemistry unit, Carl commented that explaining why vinegar and baking soda react is like trying to predict how fire works, indicating that in both cases, "You can't." This suggests that at some point he did consider the possibility of a deeper explanatory mechanism for fire, although this may have been at least partially triggered by my own questioning of his analogy. That he later made this connection shows a growing awareness of the need to move beyond descriptive comparison in analogy. Unfortunately, rather than seeking a deeper understanding of fire, he used his lack of understanding of fire to reinforce his sense of futility in trying to understand the nature of the reaction between vinegar and baking soda.

8. **One-way valves.** (What kind of one-way valve might exist in a battery?)

Carl: Like I said. It's pushed, because it's packed in there. It's all squished in there.

Ms. S.: And that pushes it out which end?

Carl: This end, 'cause this is like.... Have you ever seen one of them one-way valves that's like this? If you push water against, the water will just go down the sides and if you try to push water through it, it will open up for the water to go through.

In the next case, Carl's attribution of light speed to electrons was likely intended as a figurative way of saying, "very fast." Nevertheless, he used his knowledge of the possibility that light can travel at incredible speeds to suggest that something similar could happen in a battery. Consideration of this possibility could have led to important questions regarding possible similarities between electric current and light.

9. **Light-speed.** (Why would electricity travel at the same speed as light?)

   Carl: Because it's light speed. If I shone a flashlight in the middle of the night to the trees, it would be over like that [snaps his fingers].

   Ms. S.: So, the speed of light?

   Carl: Yeah. And this is such a short distance between the battery and the bulb. It's way shorter than this from here to the trees, so maybe it happens faster, 'cause it's not even a mile. Not even a meter.

As with the conducting gates, the glue-and-paper-ball analogy presented next provides a very descriptive visual image, but does not really help to explain sticky energy:

10. **Glue and paper balls.** (What in the battery might act as the glue associated with the source analog?)

    Ms. S.: So, what causes bumps to go on the marbles then?

    Carl: What causes bumps to go on the marbles? Well, when the marbles come back in, the energy is just pushed against them. Here's a marble here, and they go into the battery, and maybe all the energy is pushed against them, because it's bouncing around like a laser beam or whatever. And when it hits them, it just stays there.

    Ms. S.: On the marble?

Carl: Yeah. If you had a rubber piece of glue or something, and it would only stick to paper, if you threw it, wouldn't it just bounce off, or would it stay there? That's like the marble or whatever. It would hit there and stay there. Maybe it only goes to the marbles. And it just stays there, and it has to go through two batteries. It has to go through this one.

In much the same manner as the traffic analogy, the dump truck in the next case relies upon a willful driver. To make his analogy effective, Carl needed to explain how the necessary energy could have been delivered by a driver-less truck:

**11. Dump truck.** (How does the battery component analogous to the truck unload in a bulb? How does it know how much to leave? How does it know how long to wait?)

Carl: Well, maybe in that little glass bulb, marble or whatever, waits till all the energy is used up, or till its amount of energy is used up, with some good stuff left over of course, and then it goes on to the next bulb or whatever. It waits there. Sort of like, take a truck, and it unloads its stuff, and it's supposed to get another stuff, where does it go? It goes back to base and waits somewhere else for the stuff that's going to get put back into it, and it keeps on going. So maybe that truck had four or five stops to do each time, and each time it got something different. By the time it got back to base, it would have something totally different.

Ms. S.: So, after it dumps it.... Like, it dumps it in the light bulb?

Carl: Well, it scrapes it off.

Ms. S.: Which is like dumping the truck, right?

Carl: Yeah.

In the following case, Carl improved his earlier glue-and-paper analogy, but did not suggest how this might improve the transferability of the explanatory structure of his analogy. It seems that he simply preferred the image of the magnet and iron filings to the image of the glue and paper:

> **12. Circular magnet in iron filings.** (How would magnetic force hold energy on the battery component analogous to the marble?)
>
> Carl: There's a better way to explain it. Like, if you took a circular magnet, and you dipped it in a big pot of iron filings, what would happen? It would become three times its size, right? And then you put it on a really big spin, zero gravity. And you put it through a hole that's just the size of the center, the magnet. What would happen? All the iron filings would get scraped off.

In the next instance, Carl further modified his rough-marble theory, but did so on the basis of my questions. As mentioned earlier, this is an example of a generative analogy and was invented by Carl to elaborate and clarify his explanation:

> **13. Marbles wearing down.**
>
> Carl: Yeah, but some of it got scraped off, and since it's sort of magnetic to the marble, maybe it follows the marble through the track. It's spinning, and it's pulling the marble on the outside of the track. If you take two magnets on a table, you can move the top one from the bottom, right? Maybe that's what's happening. It's moving it through the walls of the wire. It's pulling it to the walls, and it's scraping off. The table is a wire, and this is a piece of energy [scraping marble along table]. It's following something. It's really fragile, and it's pulling against there. It's going to scrape some stuff off there, causing some friction.
>
> Ms. S.: But do you need to scrape off stuff in order to create heat?
>
> Carl: Not really. Just rub against it to cause friction. It's pulling against the wire, and it's causing friction against the wire, and maybe some of them get left behind.

Ms. S.: Some of what?

Carl: Some of those little things. Like, they don't exactly get left behind, but they become smooth. So, they go back onto the top, and then the bumpy ones come again, and so that just keeps on going. And so if this was the wire, and these things are invisible, maybe the wire's only actually this big, with all the energy on top of it. And so it's always going through there. 'Cause there's always a bunch of marbles [putting a handful of marbles on the table]. It's like this, and maybe the bulb is right here....

Ms. S.: So, like, these have to go through this bulb?

Carl: Yeah. The bulb is right here, and this one's already gone through, and the rest of these still have to come through. So like this. This is what would happen [pushing all the marbles through a track made of pencils].

Ms. S.: And as they're going through, are they scraping off their energy? Or they're just rubbing?

Carl: They're just rubbing. Can you hold that thought for a second? I'm going to put these back in the jar. Anyways, what was your question again?

Ms. S.: These marbles here. I just asked when you were pushing them through, were you seeing them as scraping off their energy or just rubbing to create heat?

Carl: Let's lose the energy thing. The scraping off energy.... 'Cause they could be scraping along there....

Ms. S.: How come you like that idea?

Carl: Because it's easier to explain, and you're actually preparing me very nicely, thank you, for telling my battery to the class.

...

Carl: Now I have a great idea for this. As it's going through, it goes back in, but it's still rough, right?

After it goes through a billion, zillion times or whatever, it starts to get smooth and smaller.

Ms. S.: 'Cause they're going around and around and around...-

Carl: Yeah, like, it's been worn through a couple of thousand or billion times, and it's getting smooth. Before it was bumpy and about the same size as this hole, and this is a dead battery or bulb, so it can easily fit through there. But there's nothing on it to make friction.

14. **Vinegar and baking soda gas pressure.** (What would make the pressure in the battery? Why wouldn't it explode? The balloon fills with gas. Is that also what pressurizes the battery?)

Carl: If you take air.. We were taking test tubes and putting balloons over them or whatever in Science, and then you take vinegar and put it in the balloon, and put baking soda, and put it in a test tube, and put the balloon over, and hold onto the balloon, it would cause pressure, but if it was a cork, in there it would go, "BMMMMM." What was I saying?

Ms. S.: Something about vinegar and baking soda in a balloon.

Carl: Oh, yeah. Like, not in a balloon, a cork. And that's what's in here. It's pressure. They put something in there first when they're making the battery, and they hook it up to a special machine, a charger or whatever, and it adds another thing in there that would react to it, maybe, and bulge out, and that's what pressurizes it. They don't pressurize it right away. That's my idea, yes. (Battery Interview, March 25)

The final version of Carl's battery, which incorporated many of the analogies presented here, would make a great visual on a computer screen. In many ways, however, it remains unclear how it would actually work.

Despite his reluctance to evaluate his analogies, Carl's amazing capacity for generating them in the first place cannot be overlooked. What is it that allows him to propagate and manipulate mentally such an imaginative array of visual likeness? His proclivity to summarize new knowledge and new ideas and continually to reduce them to simplest form may be important factors in understanding this phenomenon, but this remains unclear. This idea is discussed further in Appendix I.1.

Samantha's analogies are comparable to Carl's in the degree of descriptiveness that they provide, but she, too, failed to consider the applicability of her analogs:

1. **Bubble gum.** (Can bubbles have magnetic force?)

| | |
|---|---|
| Samantha: | Well.... Um.... Sort of. Like, you have a wire here and a wire here, and they're both kind of mixing around in there [pointing on diagram], and they just keep going right there. That would make a short circuit. I think so. 'Cause they'd just be together and all just going right on, just keep on going through. Unless.... Can I borrow your pen? |
| Ms. S.: | Uh huh! Maybe don't use your diagram, just draw it over here [on a separate piece of paper], and then you'll have your original. |
| Samantha: | Draw your battery [drawing], and we have the metal up here.... There's your metal. Then if, um, you had your wire going out to the light bulb and the wire going back in [drawing on paper], then, like, first there'll only be one sort of energy, like it'll be in its own little bubbles, like separate bubbles. There'd be separate bubbles in there, and then, um, they would go through the metal or whatever, then go to the wire [drawing on her diagram], then after the bulb right here, they would turn into base after the light bulb, and this would be base going back into here, and then there would still be bubbles going around except there would only be.... It would be a different kind of bubble. Like, there'd |

still be the old bubble, but this is like a new bubble, like a different kind of bubble. So, it's almost like there's a male bubble and a female bubble, except they're not necessarily male and female! Then the top would only, like.... Only the.... Like, there could be red bubbles and blue bubbles. We'll just say the red bubbles are the non-used acid, and the blue bubbles are the used...are the base [At this point in the unit, some of the students were convinced that used acid turns into base]. So then only the red bubbles would be attracted to here, so then they'd just be mixing like everything. Well, nothing would be moving when the wires weren't connected, but when you connected them up, then the red bubbles would be attracted to the top part, and they'd go through into here, and they'd make blue bubbles, and only blue bubbles would come in through here. And once all the red bubbles were used up, then the thing would just be full of blue bubbles. That would work too. 'Cause then the bubbles wouldn't be mixing. They would be in the same area, but they wouldn't be, like, touching, 'cause they would be in a little case.

Ms. S.: Okay.

Samantha: Like, if we each took bubble gum or something and stuck it around our fingers, we could move our fingers and touch the bubble gum and stuff, but our fingers wouldn't be touching, like if our fingers were the particle things, but the bubbles wouldn't really attract or anything. The bubbles wouldn't stick together, though. Almost like the magnets. They wouldn't stick together, because you know how magnets.... If you turn them one way, then they go together, but if you turn them another way, they force each other away and push away from each other. Maybe that's what the bubbles are doing. Maybe that.... Their whole force is pushing away. So, like, not half them is together and half is away...just like they're all pushing away.

**2. Sucker.** (Why would the bulb repel a certain type of bubble?)

Samantha: [finishes drawing] Then how would that work? Like that. Because if the plus and the minus, and the plus is the acid and the minus is the base, sort of like.... So if the plus attracts the acid, how is it supposed to go through both of those things [bulbs]? Let's see if it works [setting up a circuit powered by two C-cells connected in series]. It works! 'Cause, like, it can't really go through both of those little things - metal things - because it attracts [thinking] ..Hey, I have an idea!

Ms. S.: Okay!

Samantha: If it takes.... You have your battery here, and it takes all the plus, all the little acid particles. The acid knows where to go through here - I think the bulb sort of attracts all of the plus, like this side attracts the plus, and it uses all the plus, and then it turns into base and lets it go, like.... Do you know what I mean? 'Cause I can relate it to food. Like if you have a sucker or something, and it changes flavor after one layer, like they have layer suckers. Like you suck on the one layer and you really like it, like it's bubble gum or something, and then you're sucking on it, and then when that layer's gone, it turns into grape flavor and you don't like grape, so you throw it in the garbage or give it to somebody else, 'cause you really wouldn't want to eat it anymore, 'cause you really don't like grape. (Battery Interview, March 30)

**3. Bingo machine.** (What kind of force causes the energy in the battery to move?)

Ms. S.: So this pulls this out, right, so this is pulling this one, this one gets pulled out, but is it attached to this, or what makes this one go now?

Samantha: Well, have you ever seen a bingo thingy?

Ms. S.: Like to shake up the balls?

Samantha: Yeah, like to shake up the balls. And then you have all the balls down there, and then you have one ball at the top, and you take it and you pull it out, and the other ball immediately sucks up.

Ms. S.: Why? What causes that?

> Samantha: Um... Well the first ball is gone, so that space is empty and, like, it's all full of these things [pointing to diagram], so this one like automatically moves up there to find more space sort of.
>
> Ms. S.: Is something pushing it, or is it just moving because it wants to find more space?
>
> Samantha: Well, because this is pulling.... Like, if this one is in here, then this is the next one to get pulled.
>
> Ms. S.: So, it can reach this far you mean? It doesn't have to be right next door to pull it? It could be back here and still get pulled?
>
> Samantha: Yeah, sort of. Like, when this one's gone, this one gets pulled here, and it goes in and -
>
> Ms. S.: And at the same time, are these pushing?
>
> Samantha: So, like, this one gets pulled. This is pushing these away, and this is pulling them in, so they're all crowded in, and it's full. So this one will pull, and they all start to move, and then they join, and they keep on moving and moving, only it's faster, so the light bulb will light. (Battery Interview, March 30)

In some cases, it is difficult to determine whether explanatory structure should be transferred. The nature of the force inside a battery is difficult to consider. Although Carl's gas pressure analogy and Samantha's bingo-machine analogy could be challenged on the basis of their lack of an identified mechanism for producing these forces, magnetism as an unseen force seems plausible. If the students had identified implications for this theory, they could have tested its validity in that manner:

> This concept helps to account for the remarkable ability of scientists to formulate and propose hidden structure and processes in nature before they are observed more directly, such as atoms, black holes, and the "bending" of light rays. An explanatory model can allow the scientist to see a phenomenon in a new way via an analogy to a hypothesized visualizable structure that is considered to be hidden in the target

> situation to be explained. This is something that empirical law hypotheses cannot do. (Clement, 1989b, p. 359)

The use of observable implications as a source of evaluation is discussed in Section 4.3.3.3.

According to Grosslight, Unger, Jay, and Smith (1991), most students view the purpose of models to be primarily communicative:

> Approximately half of both groups said that models were for showing an object (e.g. what it looks like). The groups then diverged with the mixed-ability-7th graders saying that the purpose of models was to give you an example or demonstration of what something is or does, and that models were basically for looking at and playing with. In contrast, many honors 11th graders thought the purpose of models was to help someone understand and to teach, as well as to make things more accessible or convenient to see and / or use. Ways of accomplishing this purpose were highlighting, simplifying, and omitting information from the model or changing the size, location time, or view of the referent. (p. 804)

It seems likely that the types of models that students describe would mirror their own experiences with models. It would be interesting to see how the students in this study would describe models after having been involved in generating, evaluating, and reflecting upon their own. Grosslight et al. (1991) suggested that

> ...giving students chances to use or design models for multiple purposes may be a natural way to lead them to reflect on a variety of epistemological concerns including the purpose of one's inquiry, the nature of what one wishes to communicate, explain, or understand, how one is informed, and the interplay between reality and one's ideas about it. (p. 820)

Although Carl's model grew substantially over the course of his interview, he often made comments that indicated his belief that he was merely sharing ideas that he already had. Comments indicating frustration with being able to express what was going on in his mind further suggest the frequent visual nature of his models and reinforce the need for descriptive analogies to describe them.

Just as analogies may be applied in cases where they are not applicable, discrepancies or gaps may be explained away with, "That's different," even when the student has not identified a reason for this sort of dismissal. This was evident in Carl's gate analogy. In the following dialogue, Carl's refusal to accept Jordan's argument on the grounds that the highway is "just an analogy" further illustrates his lack of understanding of the need to evaluate the transferability of the analogs he uses to describe his ideas. Frank, Robert, Samantha, and Carl all contributed to further mapping of the analogy and debated whether the type of behavior that it suggests would solve the mixing-marble problem, but none of them directly addressed Jordan's concern. Carl is correct in his assertion that not all components of an analogical relationship need to be transferable. However, his unwillingness to consider carefully which parts are essential to the explanation provides further evidence of his lack of metacognitive understanding of the importance of ensuring that those parts of the analog upon which proposed explanatory structure rests need to be appropriately mapped. This is the basis of Jordan's persistent argument against the traffic analogy. Despite Carl's protests, the points that he identified were indeed salient to the discussion. They prompted Carl to clarify his theory, which he did by means of a roller-coaster analogy. Although Jordan's argument fell apart when he suggested the possible destruction of the analog track, his initial arguments were sound:

Frank: Yeah. And then there will be a light bulb here, and there will be another light bulb here, and then there'll be wire like that. And the same thing will happen. Energy will come up like this. It'll go up, and this time though, it'll go up into the bulb, and they'll go around, and it'll come, and it'll pass each other in this wire at the same time.

Keith: That's a hot wire.

Robert: It's still going to be a hot wire.

Jordan: So, you make a hot wire that way.

Frank: They're not mixing.

Jordan: No, but there's two coming here, and it goes up in there and goes here, and they're still alive so...a hot wire.

Frank: They'll just pass each other. They're not mixing.

Robert: They have to pass each other through the bulb, too.

Frank: No, they don't, 'cause they're at the same speed. They cross each other at the same time, and these two will meet in the bulb and they'll crash. See?

Jordan: The first one's coming through will cause a hot wire because -

Frank: No, it won't, because they're not mixing in here. How can it cause a hot wire if they're not mixing?

Robert: Well, they are mixing.

Frank: No, they aren't. They're passing each other.

Jordan: You said that this one's dead, so it doesn't cause a hot wire, so that goes against that one.

Frank: Jordan, Jordan, Jordan. This is the wire coming from this side, and it's going on the bottom of the wire, and this one is going on the top of the wire.

Samantha: It's like a highway. If you have a car coming this way and a car coming this way, and they go, "BOOM," well they're going to crash, aren't they? Well, if he doesn't want the wires to mix, well then, that's sort of like two sides of a highway. One goes this way and the one goes the other way.

Robert: But then shouldn't you have two roads? But he only has one road.

Samantha: But, if you take, like -

Carl: We've only got one road out here, and we can still pass, right?

Samantha: If you take a wire -

Ms. S.: Hey, guys. One at a time.

Samantha: Maybe there's two sides in the wire. Like, there's two different parts in the wire. Like, you have one going one way and one going the other way, so then it can go like Frank says. And it can go through.

Jordan: But, still, the wire. How can there be two highways? There would have to be people driving these electric things.

Frank: [mock-choking Jordan]

Carl: Jordan, do you know what an analogy is? It's something that's different, but it -

Ms. S.: Okay, I believe he's challenging your analogy.

Carl: I know, but he's saying if it's like a highway.... We're not saying....

Frank: It's so small, you can't see it.

Jordan: But still, there would have to be two little highways in there -

Ms. S.: Okay, sorry, Jordan? Let's let Jordan finish, okay?

Jordan: There would have to be two little highways in here, and you would have to have people driving these little things.

Frank: No, you wouldn't. The energy just goes through them.

Carl: The shock pushes it....

Frank: Yeah, the shock pushes it.

Robert: But the shock doesn't guide it. It just pushes it.

Jordan: Yeah, the shock just pushes it.

Frank: The wire guides it.

Jordan: How can the wire guide it?

Carl: Well, hey. Take a roller coaster, and even if there's a steering wheel in front, it doesn't work, right? Because it follows the track. The wire is like a track. It follows the track.

Jordan: So, if that track just fell apart all of a sudden one day -

Frank: That's why it doesn't work then.

Jordan: If it was a non-rechargeable battery, you would just say, "It must be the battery," and just chuck it.

Frank: No, because you'd have to cut the wire.

Jordan: So, but, still, okay, now a battery goes dead, right? The rail wire, this derails, it just goes off track, and it crashes. So, it would be like, okay, this is a hot wire.

Carl: You said the battery was dead, right? If the wire breaks, you can see it if the wire breaks.

Jordan: You would predict that it was dead, because the light bulb burnt out.

Carl: You can see if wire breaks. (Class Discussion, March 11)

It is important to note that although his comments reflect Level 3 AR, Jordan had not generalized his understanding of analogical reasoning in a manner that warrants a general classification at this level. His challenge of the highway analog would reflect

Level 3 AR if he used such a strategy consistently and not just when he had immediate difficulty with the particular analogy being proposed.

#### 4.3.2.2.4. Proxy abstractions.

> *I turned the page. The answer was, for the wind-up toy, "Energy makes it go." And for the boy on the bicycle, "Energy makes it go." For everything, "Energy makes it go."*
>
> *Now that doesn't mean anything. Suppose it's "Walkalixes." That's the general principle: "Walkalixes makes it go." There's no knowledge coming in. The child doesn't learn anything; it's just a word!*
>
> (Feynman, 1985, p. 297)

As the students attempted to develop explanations for circuits and for the vinegar and baking soda reaction, there were several cases in which they did so by appeals to poorly understood abstractions that they used as substitutes for more complete explanations. Although there is some overlap with Level 2 FOI's understanding the point of asking, "How...?" and "Why...?" I have included this as a section within Level 2 AR in that when using a proxy abstraction, the applicability of explanatory transfer is assumed rather than evaluated. The refusal of many class members to accept these vague proxies may partially demonstrate their growing awareness of the importance of deeper levels of understanding, although unfamiliarity with the suggested abstractions likely plays a large role in driving their questions. The ability to question proxy abstractions does not seem indicative of a more general understanding of the need to validate analogical relationships.

A proxy abstraction can only be evaluated if it is identified and reified with concrete examples. If the abstraction were formed by the identification of common structure among a variety of related phenomena, the identification of these examples is typically something that students are able to do. In some cases, however, understandings may have been acquired as a complete (albeit superficial) structure, in which case they may have very little knowledge to support or reify their understanding.

Carl reads a considerable amount of science-related material and seemed particularly prone to using abstractions about which he had only vague understanding. During his battery interview, he attempted to use abstractions for "volt," "circuit," and "conductor," none of which he really understood. With a little bit of prodding, however, he did question himself on the meaning of both a conductor and a circuit:

| | |
|---|---|
| Ms. S.: | And what happens when you do this with real batteries? What would happen to the bulbs in that circuit? |
| Carl: | They'd go brighter. |
| Ms. S.: | Can you explain that? |
| Carl: | Maybe because there's two billionths. 'Cause there's one billionth here, and - |
| Ms. S.: | And why do they go out more at a time when there's two hooked up? |
| Carl: | Because there's twice the power. There's twice the amount. There's three volts instead of one point five volts. |
| Ms. S.: | Define a volt. |
| Carl: | A measurement of energy? |
| Ms. S.: | So, what are these volts doing that makes more go into the bulbs, then? How come when you put two in a row, more would go out at a time? |
| Carl: | 'Cause maybe it's putting more bumps on the marble? |

Ms. S.: Why?

Carl: 'Cause there's two of them. It's putting twice as many bumps on the marble.

...

Ms. S.: So then what happens when you hook the wire up?

Carl: It creates a circuit.

Ms. S.: Questions for yourself.

Carl: What is a circuit?

Ms. S.: Okay.

Carl: A series of wires and components hooked up to a power source.

Ms. S.: Okay. Keep questioning yourself.

Carl: Uh, I don't know. I understand it. It's just hard to explain to people. Like, if we could automatically transfer energy then, "ZAP!"

Ms. S.: Wouldn't that be nice? Could you try it? I'd sure like to hear what your theory is, and I'm afraid I don't have an electrode to hook up to your brain.

Carl: Um.... Well, I pretty much explained it all. I don't know if you have any questions or not.

Ms. S.: Well, I'm wondering why wire.... Like, what's so special about wire that whatever's in here.... Is it the energy coming out of here?

Carl: Yeah, but it has no place to go. It's packing in here.

Ms. S.: So, why doesn't it work if I hook a piece of string up to it?

Carl: 'Cause string doesn't conduct electricity.

Ms. S.: Why?

Carl: 'Cause metal does.

| | |
|---|---|
| Ms. S.: | Yeah, I know it does, but that's not what I asked. |
| Carl: | Why doesn't it work if you do what? |
| Ms. S.: | Why doesn't it work with string? |
| Carl: | Because string doesn't conduct electricity. |
| Ms. S.: | So, define "conduct electricity." |
| Carl: | Um. |
| Ms. S.: | In terms of your model. |
| Carl: | It'll let the energy go through it...pass through it sort of. |
| Ms. S.: | So, why wire and not string? |
| Carl: | Um, if you get string wet it'll work. It should. |
| Ms. S.: | Why wire and not dry string? |
| Carl: | 'Cause string isn't made of metal. |
| Ms. S.: | So, what's so special about metal? |
| Carl: | Metal conducts electricity. We're going around in circles here. I don't know. Conduct electricity. Um, I don't know. It's kind of hard to explain. |
| Ms. S.: | Do you have a picture in your head? (Battery Interview, March 25) |

At this point, Carl presented the gate analogy described in Section 4.3.2.4.

In the following situation, Matthew demonstrated an unwillingness to allow "neutralization" to substitute for a detailed description of what happens to baking soda when it is mixed with vinegar:

| | |
|---|---|
| Matthew: | This is quite far back about Robert. How does the baking soda disappear and why? |
| Robert: | Uh.... It doesn't disappear. It just sinks to the bottom. |

Matthew: You said before it disappears. It dissolves.

Robert: The vinegar.... The vinegar uses it.

Matthew: How? It doesn't use it.

Carl: It's a neutralizer. It neutralizes it.

Matthew: How?

Carl: Well, I don't know. You'll have to make up a chemical compound. (Class Discussion, April 20)

Although Carl seemed to realize that the nature of the chemical reaction is somehow related to the process of neutralization, his subsequent chemistry interview suggests that this is a concept regarding which he had little understanding.

As was considered in Section 4.3.2.3 in the context of the more general discussion regarding the importance of evaluating the validity of analogical relationships, too much attention to unpacking analogies may actually be detrimental. In many ways, Carl made productive use of abstractions for which he had only vague, general understanding to formulate initial ideas regarding the phenomena he was trying to explain. However, once he did so, he needed to consider the smaller networks that formed the abstractions with which he was working. In his chemistry interview, Carl was reluctant to consider neutralization at a deeper level even after he had developed quite a detailed macro-structure to describe the vinegar and baking soda reaction and was at a loss regarding how to further develop it. At this point, more clearly defining what he meant by "neutral" should have been a worthwhile activity:

Carl: So, maybe the powder part of it in the water that's dissolved - dissolved in the water - maybe that's what reacts with this. Not the vinegar-water liquid, but what's dissolved in it.

Ms. S.: Acetic acid is the stuff that's dissolved. So, you're saying that it's the acetic acid.

Carl: And not the water. And maybe it becomes inert, boring, useless. You know what inert means, right?

Ms. S.: I wouldn't have defined it as boring or useless. I'm not sure what you mean by it.

Carl: Inert means "no use."

Ms. S.: In chemistry, it means it doesn't react.

Carl: Well, true, but I've heard it explained either way.

Ms. S.: Well, however it's explained, just make sure that you explain what you are thinking.

Carl: It's not useful. It's neutral.

Ms. S.: So, how do you mean that it's not useful? In your theory?

Carl: It's all used up.

Ms. S.: Oh, I see. It's not useful in terms of further reactions?

Carl: Yes. Then it becomes neutral, 'cause it's neutralized.

Ms. S.: Meaning?

Carl: It doesn't have a pH, really, except for seven.

Ms. S.: But in terms of the particles, what do you mean?

Carl: They become harmless.

Ms. S.: What's happening to the particles?

Carl: They're being broken up.

Ms. S.: And why does that make them neutral?

| | |
|---|---|
| Carl: | Because.... I don't know. All I'm saying is that the water is left over, and everything else is neutral. It's evaporated - not evaporated, but whatever it's called. Dissolved. Whatever it's dissolved in – it's most likely distilled water - so that's what's left, and distilled water is exactly neutral, right? So, everything else is used up except for maybe a little bit of the basic stuff. |
| Ms. S.: | But what do you mean by "used up"? What happens to the stuff to make it neutral? |
| Carl: | I don't know. |
| Ms. S.: | Can you think of something? |
| Carl: | It's used up. |
| Ms. S.: | You mean like it disappears, gone, vanished? |
| Carl: | Either that or it's broken into atoms. It takes different kinds of atoms to make molecules. (Chemistry Interview, May 25) |

At this point, Carl may have done well to integrate his explanation with the model of rearranging particles that he had already developed to help explain the reaction. That he did not do so may have been due to the flippant attitude that he displayed during this interview, which may in turn have been at least partially related to his lack of understanding of the nature of subjective knowledge (This is discussed in Sections 4.3.1.4 and 4.3.3.2.3).

Carl's initial definition of chemistry was "mixing two or more different chemicals to make something different" (Class Discussion, March 25). As other class members suggested examples and analogies intended to clarify their collective definition of chemistry, Carl remained silent. His reticence this situation seems much like that of students asked to explain why a mathematical algorithm works when they are perfectly content to accept that it works and take advantage of its functionality.

One key to moving beyond the use of proxy abstractions seems to lie in the recognition of one's own ignorance.

In the following segment from her battery interview, Samantha did a very good job of identifying the gaps in her own knowledge of certain abstractions and deliberately addressed them. As she explained her idea, she mentioned broad concepts for which she had deliberately developed more specific definitions or for which she indicated that she did not yet have complete definitions (i.e. "acid," "base," and "working"). This may have been the result of previous classroom discussions during which she was questioned on these or similar matters. In any case, it certainly demonstrates her ability to formulate a broad explanation that relies on abstractions that she apparently intends to consider in greater depth:

> Ms. S.: Okay? And that's, so first of all just explaining that....
>
> Samantha: Okay. Um.... My battery. This is how I think it works.... Um.... The top of the battery is all metal and down the sides is all coating and across the bottom it's metal, too, like there and right there [pointing to diagram of battery], and I think there is a cardboard divider in the middle of the battery, so right there [again pointing to diagram of battery]. In the top half of the battery is acid, and I don't have the definition of acid yet, and the bottom half is empty. When the acid goes into the circuit, it turns into base, but the acid turns into base after it goes through the ball, so it goes through the ball, and after then when it's all used up, then it goes into the base.
>
> Ms. S.: So you have a one way [motioning in a circle]?
>
> Samantha: Yeah. And.... Um, the base is like used energy. When the base goes back into the battery, it starts to harden. It takes the base about 48 hours to harden. The acid in the top half keeps on working, and I have a definition of working..... The acid is going through the circuit and turning into base, so it keeps on [motioning to diagram]

> going through that as long as my circuit's hooked up. So as soon as I pull the wires away, then nothing works. Everything stops. And then, um, after about 48 hours all of the acid has turned into base and is hardening in the bottom of the battery. As the base hardens, it expands, and the cardboard starts to crack. So, like, um, I was just, um, about 48 hours, but um, I don't know how long a battery works. So, like, maybe it's 68 hours or so, I don't know. I'll have to maybe test that sometime. But I was just using 48 hours, 'cause as soon as, after, like, as soon as the battery is, like, all the acid's gone, then it doesn't work anymore. It's dead. (Battery Interview, March 30)

As the students learn to consider the non-corresponding elements of proposed analogies more carefully, to develop bridging analogies, and to identify predictive implications, the importance of validating analogical relations may become more apparent to them. These strategies are discussed in the following section.

#### 4.3.2.3. Level 3: Evaluated equivalence.

> *Recent analyses of Darwin's notebooks have suggested that a more indicative hallmark of genius than pure eureka episodes is the ability to generate tentative analogue models as a starting point and then to carry out the long struggle of a cycle of repeated generation, criticism, and modification or rejection that is necessary to construct a successful new theory.... The most viable powerful form of scientific reasoning may lie in the ability to engage in such a dialectic cycle, rather than in the ability to invent a completed model in one stroke.*
>
> (Clement, 1989b, p. 380)

To determine whether the explanatory structure of a source analog is applicable in the target, students must compare both similarities and differences that exist between the analogs. If the differences are part of the explanatory structure that is being considered for transfer, the analog does not apply. Consideration of why selected components should apply in both a source and target analog may be done simply by seeking common causal mechanisms in each. However, such mechanisms may not always be apparent. In some cases, a third case that the student sees as connected to both the source and the target is used as a means of evaluating this relationship: Clement (1981) referred to this strategy as "bridging." Identifying observable implications of a proposed explanatory structure may also allow the transferability of explanatory structure to be evaluated. The ability to identify predictive implications has a developmental history of its own and is discussed in Section 4.3.3.

Analogies for which significant differences are identified need not be discarded, and often the identification of these differences instigates modification of the analog in a manner that remediates its non-applicable aspects. Clement (1981) referred to analogies generated in this manner as "generative transformations." At Level 2 AR, transformations were often based on the need to develop consistent visual images. At Level 3, they also focus on underlying explanatory structure. The strategy itself is no different at this level. Differences in the types of transformations developed merely reflect the nature of the difficulties that are perceived in the original analog relationship.

None of the students in this study demonstrated consistent efforts to validate the analogies that either they or others generated. However, there are several instances in which they did so when a specific analogy seemed particularly implausible, thereby making apparent the need for justified arguments against it. That they were able to make use of this strategy in certain areas suggests that it may be something that they could learn do more consciously if they were guided to reflect upon its productive use in familiar contexts.

The use of animistic analogies seems a particularly promising arena in which the importance of validating explanatory structure may be emphasized. Animist explanations are pervasive, and students usually do not actually believe that the phenomena that they animate are living or willful. With this basis, it is not difficult for many students to begin to see that explanatory structure that relies on animist intent is not valid, even when they emphasize the non-animate nature of the target analog. An alternative causal mechanism is needed in these cases. Although the willful components of the explanatory structure of explanations based on animated components did need to be dealt with in many cases, many animistic analogies did contain applicable elements that prompted discussion of some very significant features of the phenomena being studied. These ideas are considered in Section 4.3.2.3.1, which is dedicated exclusively to a discussion of animism as a productive context for the development of students' analogical reasoning skills.

In the cases that follow, the students clearly demonstrated their ability to consider the applicability of proposed analogs. Nowhere, however, did they identify this strategy in a more general form, and it is certainly not one that any of them used consistently. Recent observations of Grade Five students suggest that at least some students are able to articulate a generalized understanding of the importance of verifying the applicability of analog relationships when they are asked to reflect upon contexts in which this was done effectively. There is also evidence that they can learn to distinguish mapping from verification. Because I did not have a clear understanding of the distinction between these concepts at the time that this study took place, I did not effectively guide student reflection regarding this matter. Further research is necessary to determine whether understanding the importance of transferable explanatory structure is something that all students at this age are able to accomplish and whether the articulation of this more generalized understanding could then lead to more systematic validation of analog relationships in a variety of contexts.

In each of the examples presented in this section, a student attempted to justify his or her ideas on the basis of similarity to another situation (i.e. by analogy), and another student challenged this basis. The challenges were typically based on the nature of similarity between source and target analogs and went beyond arguments regarding understanding of the source analog that were common at Level 2 AR. In rare cases, bridges were used to strengthen these arguments, and evidence of generative transformations resulting from successful challenges were sometimes apparent.

In the following example, Matthew equated Frank (A) and Frank (C) circuits on the basis of his belief that if one works, so should the other. Frank's explanation of what he perceived as salient differences between the two portrays an attempt to evaluate the validity of the proposed similarity:

Ms. S.: Matthew is saying if Frank (A) works, then that one, Frank (C), should have worked, because he's saying it's the same thing.

Frank: It's not exactly the same thing. This one is touching this battery to give this more power, right? And so this will get more power to this light bulb.

Ms. S.: Okay, but why doesn't that work in Frank (C)?

Frank: Because actually the.... These two. They're smushing the wires together.

Ms. S.: Okay, but what Matthew's saying is whether the wires are smushed together or not, the current can travel through the wires from the positive to the negative through the wires, 'cause it all works. Is that right, Matthew?

Matthew: Yeah...

Robert: Then when you make a simple circuit like this, [drawing on blackboard], then this metal is touching this metal through the metal on this, but the light still lights up. (Class Discussion, January 12)

In the next example, Samantha questioned the applicability of a marble analog to energy particles and suggested that perhaps energy is different from marbles in that it might keep on moving rather than eventually stopping (a generative transformation):

Samantha: Okay, like what Robert said. The "active strength or force". Maybe, like, if you have to shock things, then it shocks the energy or whatever, and the energy keeps on.... Like, it goes.... That shocks it out of the battery, but then, would shocked energy keep on moving? Like, when marbles hit other marbles, they hit them, but they only move a little bit. Like, so maybe to keep the bulb lit constantly, like, it moves by itself, the energy a little bit, maybe? (Class Discussion, March 16)

Later in the discussion, Rebecca identified and mapped a possible relationship between magnets and electricity in wires. Carl took her work one step further by questioning the degree of similarity between the two situations:

Jennifer: I just found something out with the magnets. Okay. On the magnets, I named this side A and this side B. Okay? And I found out if you take a side A and a side A, they will repel. You can't push them together. But if you take a side A and a side B, they'll go together.

Samantha: What about side B and side B?

Jennifer: Side B and side B is the same thing. They won't work.

Rebecca: So, that's like a negative and a negative and a positive and a positive.

> Carl: Maybe, wires are backwards. Maybe positive attracts positive and negative attracts negative. Maybe the wires are opposite of batteries. (Class Discussion, March 16)

Here, Carl's willingness to question the applicability of Jennifer's analogy is apparent. Although doing can be both legitimate and necessary, because he fails to identify a reason why it is any more likely that magnets and wires should be different than alike, Carl could be challenged with the WWTH formulation discussed in relation to Level 2 FOI (Section 4.3.1.3.3). This provides a hint of the complexity of the interplay that exists between the three frameworks.

Had Jennifer reversed the labels on one of her arbitrarily labeled magnets, they, too, would have appeared to behave in a manner opposite to that which she suggested. The use of a third magnet to determine which poles were actually alike and different could have confirmed her original findings.

Argument facilitates the development of bridging analogies, which act as effective persuasive tools to convince others of the validity of a particular analog relationship. Even so, bridging analogies were not commonly used by the students in this study. This is not surprising in light of the fact that they worked primarily at Level 2 AR. Schultz and Clement (1994) documented what appears to be similar use of bridging analogies by high school physics students, but it is unclear whether the students in their study were consciously aware of the need to validate the analogies that they used. For the students in my study, it seems likely that this awareness could lead to an increase in their use of bridging analogies. They are able to construct them, but do not see the need.

There were occasions when I developed bridges in attempts to help the students consider alternate ideas, and they were able to consider these arguments. However, I did not adequately encourage reflection on the nature of this strategy, and the students did not articulate an understanding of its use. In the following example, Jennifer insisted that "mixing" is all that is necessary for vinegar and baking soda to create a gas. I challenged this idea with an analogy to salt and pepper, but she rejected this association. As a result, I modified the analogy to remove the problematic spice element and thereby created a bridging analogy:

> Jennifer: It mixes.
>
> Robert: See it's mixing here, but that doesn't tell me how the gas is made.
>
> Jennifer: Yeah it does. It's mixing.
>
> Ms. S.: Okay, but if you mix salt and pepper, does it make gas?
>
> Class: No.
>
> Ms. S.: So, how come this makes gas?
>
> Jennifer: The salt and pepper are spices, right? They're like two of the same thing.
>
> Robert: But you're saying these two are the same thing except different.
>
> Ms. S.: Well, if you mix sand and salt. Would it make a gas?
>
> Jordan: No, they're neutrals.
>
> Ms. S.: But if you mix salt water and sand, would it make gas?
>
> Jennifer: You go to the beach, right. And there's lots and lots of waves, and sometimes -
>
> Robert: That's foam from hitting the rocks.
>
> Jennifer: It's mixing.
>
> Keith: That's air and the water making air bubbles. (Class Discussion, April 22)

Recent observations of Grade Five and Six students have highlighted another obstacle in generating effective bridges. The students had been trying for some time to explain why, after burning a piece of paper inside a jar and sealing it with a peeled, hard-boiled egg, the egg would pop into the bottle. At this point, the most popular explanation centered around a hypothesized reduction in pressure created by the consumption of oxygen during the burning process. One of the students had recently read about a similar demonstration that used hot water as the heat source. She challenged the fire theory on the basis that only the heat (not the fire) was necessary to make the egg go into the bottle. However, the class had already observed several other phenomena that used boiling water as the source of heat and had noted similar results in these situations. Why had nobody made this connection earlier? All class members had heated an Erlenmeyer flask with a small amount of water in the bottom, covered it with a balloon, and watched the inside-out balloon inflate inside the flask. Surely this is not so different from the egg-in-the-bottle phenomenon. Yet, for the students, the connection between the balloon test and the egg test was not apparent. Had they noted this relationship and used it to generate the idea of using boiling water for the egg-in-the-bottle event, this newly created event would have constituted a bridge. In this case, the difficulty was not rooted in an inability to form or comprehend bridges, but in a failure to perceive an apparent bridge as analogous in the first place.

#### 4.3.2.3.1. The special case of animism.

Animistic descriptions of causation were very common in the students' explanations. Some aspects of these analogies were applicable in that the explanations based upon them were independent of the animist nature of the source analog. In other instances, the dependence of explanatory transfer upon animated components in the target analog necessitated the modification or rejection of the source analog for their effective use. When this was done, the analogies served as useful starting points from which non-animated explanations were developed. There were even some cases in which the students genuinely considered the possibility that the target components might be living things, which is actually a more rational method of thinking than uncritical rejection of animism. Regardless of whether explanatory transfer is in fact justifiable, it is important that the students learn to carefully consider their reasons for justifying, modifying, or rejecting animist explanations. Because animist explanations are used pervasively and are often challenged by other students, they provide a promising context for student reflection on the importance of the more general process of verifying the applicability of analogy.

#### 4.3.2.3.1.1. Wholesale rejection of animism as irrational activity.

Carey (1985) discussed the growth of understandings in a variety of foundational areas such as "the shift away from egocentricity, the growing appreciation of the distinction between appearance and reality, changes in content of such basic concepts as causality, and so forth" (p. 488). She identified animism as an important factor contributing to student understanding of causality:

> I call this third class of putative differences *foundational* because almost every particular scientific advance involves interalia [sic] some distinction between relatively surface appearance and some deeper reality and some changes in the causal mechanisms believed to apply in the world. The failure to grasp the distinction between appearance and reality or that between animate and purposeful causality as opposed to mechanical causality would certainly affect learning in a wide variety of domains. (p. 488)

It seems likely that avoidance of animistic explanations is at least partially domain-specific. Without an abstracted decision to avoid animism per se, even adults resort to it or to teleological explanations when limits on their knowledge restrict physical-mechanical explication:

> ...A host of ancient scholars thought the stars alive. This was also the position of Origen, of St. Ambrose (the mentor of St. Augustine), and even, in a more qualified form, of St. Thomas Aquinas. The Stoic philosophical position on the Sun's nature was stated by Cicero, in the first century BC: "Since the Sun resembles those fires which are contained in the bodies of living creatures, the Sun must also be alive." (Sagan, 1993, p. 32)

The difference, I think, between scholars of the past and those of today is that today's have developed the habit of always questioning animistic notions. Through repeated refutations of animist belief, a more general belief in physical-mechanical causation has emerged in the collective beliefs of the scientific community. This generalized form of knowledge is based on metacognitive reflection on a pattern of thinking that has been repeatedly discredited and has therefore become an abstracted principle that consistently guides modern perceptions of causation.

It is important to realize that children should not be expected to abandon animistic beliefs wholesale. The decision to attribute such qualities to a particular phenomenon should be carefully considered. In some cases, such as the behavior of a mixture of yeast, water, and sugar, ostensibly non-animate entities do behave the way that they do because of animate qualities such as eating and breathing, possibilities that children opposed to animism on a broad and non-reflective scale would likely not consider. Assumptions involving animist causation are problematic, as are assumptions about anything.

During one of the initial class discussions of the chemistry unit, animistic explanations were used extensively as the students attempted to explain the vinegar and baking soda reaction. This tendency was very evident in the description of the reaction as a battle between the vinegar and the baking soda. Frank referred to the carbonate trying to "kill off the acid" (Class Discussion, April 20). Later, in response to Robert's question regarding why the vinegar is the one moving around under the microscope if the baking soda were the one doing the killing, Frank commented, "I know, but yeah, it's trying to, but there's more vinegar, so it has a harder time to try and then the vinegar takes over." The conversation continued with nobody challenging the animism evident in these statements until Robert said, "Well, won't the baking soda die? Like the ones that didn't get any food, won't they starve? [if there is more vinegar than baking soda]" This triggered a fairly extensive discussion regarding the motives of baking soda and vinegar that included a genuine consideration of the living vs. non-living status of the reactants:

Class: Well, how do you know they're alive?

Frank: Well, are they alive?

Robert: Well, they're eating stuff, right?

Frank: It's cal.... What's it called again?

Ms. S.: Calcium carbonate.

Frank: Yeah.

Ms. S.: Sodium hydrogen carbonate.

Robert: Well, if they're eating stuff…so -

Frank: They're more like dissolving it.

Robert: But then they're not alive. They're not eating…

Frank: No, they're not alive. They're dissolving.

Robert: The vinegar's dissolving it.

Frank: Yeah, but I only said if you put more baking soda in, then the baking soda is dissolving the vinegar. There's not enough vinegar to protect itself.

Robert: How does the vinegar protect itself? With a shield? [Here Robert takes his turn at arguing against animism.]

Frank: No. It protects itself, 'cause if you have more vinegar, then it can take over so, right? 'Cause there's more of it, so it needs more of it to protect it. It's like an army, see.

Frank's comments seem to indicate that although he chose animate analogs, he was not convinced that the animate nature of these was part of the transferable explanatory structure. His willingness to ask the question, "Well are they alive?" triggered a very important discussion that was much more rational than outright rejection of animism. It also suggests that, "What is life?" may be an important topic on which to focus conscious attention very early in elementary school, perhaps in response to situations such as the one described above. This understanding could undergo considerable elaboration and refinement over time as students come to appreciate more fully the complexity of a question for which even biologists do not have a definitive answer (Monastersky, 1998).

#### 4.3.2.3.1.2. Animistic analogies not dependent upon willful components.

That the animate part of the battle analogy discussed in the previous section is non-transferable need not suggest that the analogy is of no use. Discussion of the battle analogy continued for some time, and prompted the students to consider the relative strength of vinegar and baking soda and the possible effect of using different amounts of each substance. In the following instance, Frank appeared to be thinking of the reaction as a one-to-one battle, whereas Robert's suggested the possibility that one strong particle could take on two weaker ones. The use of this sort of analogy need not assume the attribution of independent will to the particles:

Class: Yeah, yeah. How does -

Ms. S.: Okay, hey, let's let him finish. He's right in the middle of something.

Frank: Okay, there's a thousand guys here and a hundred guys here, right. So, let's say these guys come and attack first, and there's only a hundred of them, so this is a small group, and there's this big group over here, and they just come in and start to ammo, and they're gone, right?

Robert: Well, what if those hundred guys are stronger than those thousand?

Frank: Well, then there's still more guys.

Robert: Yeah, but it doesn't matter. If you've got an army of a hundred and an army of a thousand, and this army of a hundred is of dragons and this is of ants, well then your army of dragons is going to win, right?

Frank: We're not talking about dragons. We're talking about vinegar and baking soda. I'm just using this for an example.

Robert: So, what if you've got a hundred vinegars and a thousand baking sodas but the vinegar here are stronger than the baking soda over here?

Frank: How can it be when you don't have enough.... So it'll have to.... Okay.

Samantha: There's super-power guys!

Carl: They're on super-steroids!

Samantha: Yeah. Like if you have three girls, no offence on girls, but I'm just going to use us. If you have three girls, and then you have four guys, guys are known to be stronger. Like, if you just take us, three girls and three guys, well guys are known to be stronger. Three guys and four girls. The guys are known to be stronger, right? Well, they can take us over. There's less of you, but there's more of us, right. You guys are stronger than us.

Robert: Yeah, but, if the girls have a more effective method than the boys...-

Samantha: Robert, I'm trying to be with you on this.

Ms. S.: Okay.

Samantha: Like, I'm trying to say that the baking soda.... If you have -

Carl: But baking soda is a neutralizer. And that's why if you take vinegar and put it in a petri dish and test it with HP [pH] paper, it's going to show up as an acid. And you put baking soda in it, it's going to show up as a neutral base.

Samantha: What I'm saying, is just what Robert said. That what if you have so much acid and so much base, like what Frank and Robert are explaining. I'm just trying to help Robert out.

Frank: [at front of room] Let's pretend there's vinegar over here, right? I mean baking soda over here, and it's fighting vinegar, but vinegar's not a very strong acid, is it? So they're sort of fighting like equal.

> But we're using vinegar, right, so let's say alcohol. Which one is going to be stronger, right? This one -
>
> Carl: Baking soda. Alcohol isn't an acid, is it?
>
> Ms. S.: Did anybody test alcohol?
>
> Frank: Where's the petri dish?
>
> Ms. S.: Should be some on the cart there, yeah. (Class Discussion, April 20)

It is possible that the students actually regarded the components as willful, but it seems more likely that "strength of acid" is something that they had only considered superficially at this point. This is more likely an example of a proxy abstraction than of animist causation. They needed to elaborate their ideas, but the animist starting point could have proven very useful.

#### 4.3.2.3.1.3. Animistic analogies dependent upon willful components.

Even the students who generated animistic explanations that relied upon willful components typically did not truly believe that the target components could act in a willful manner. It appears that the students who used them simply did so as a means of explaining what was happening. This is a classic example of Level 2 AR strategy. If explanatory structure is dependent in this manner, the analogy must be either rejected or modified to make it applicable.

In the following case, Jennifer attempted to draw connections between the animate parts of a source analog and the inanimate parts of the target. This need not suggest that the analogy would have been better avoided. Had she further developed the analogy to determine the ways in which it was accurate and the ways in which it was not, she may have been able to modify it and use it more productively. Robert's questions started to push her in this direction, but he abandoned his line of questioning (which is rather uncharacteristic of Robert):

Jennifer: What happens when you mix baking soda and vinegar? I think that when you mix baking soda and vinegar some sort of strange gas gets created and rises into the air. You have a bottle with baking soda in the bottom. You have a balloon ready. Put some vinegar in and put the balloon over it. Then it blows up. It doesn't pop or anything. Sometimes it looks like there is no baking soda even though there's lots. When the vinegar dries up, the baking soda shows up. Robert?

Robert: What is this strange gas?

Jennifer: I knew you were going to ask that! First the vinegar and baking soda creates the gas when it mixes together.

Robert: What is the gas?

Jennifer: Um.... Well the gas.... You know, like, when things collide. People hit each other, right? Their fist beats their face or whatever. That hurts, right? And then they usually cry or whatever, so when the vinegar hits the baking soda, it will -

Robert: Start to cry?

Jennifer: Sort of, yeah. It cries, then. Then you create the bubbles, 'cause you're boiling mad, and then the blood stinks. Okay?

A little later:

Andrea: Jennifer, what did you say about what the strange gas is?

Jennifer: Like, for the answer? The force of the baking soda and vinegar creates the gas.

Robert: But still. What is the gas? The force of the baking soda and vinegar is the gas, but how is that making the gas?

Jennifer: Okay. Here's your little baking soda bunch [drawing on blackboard]. Then here comes the vinegar. And it gets mad, because it's hitting it like, charging into it. They collide, right? So, each one is getting mad at the other, right? The vinegar has to hit the baking soda harder than the baking soda hits the vinegar.

Robert: Why?

Jennifer: Okay, forget that. One has to hit the other harder than the other one.

Robert: Why?
Jennifer: I'm getting to it. You know the vinegar has to drop in, and you already have the baking soda down here, and it's all nice and flaky, right? Well, this has to drop in, and it can come in super-hard, right, and hit the baking soda, which will make it mad.

Robert: Why?

Jennifer: Why would it make it mad? Do you get mad if people hit you?

Robert: If they're my friends, kind of. Not really.

Jennifer: Would you get mad if Amy cut your hair off?

Robert: Oh yeah.

Jennifer: Well, same reason with the baking soda and vinegar. They get mad at each other. Just imagine. Anything else? Andrea. (Class Discussion, April 22)

In the next instance, Robert challenged what he perceived as implied animism in his own analogy and invented a new analogy to compensate for the lack of selection mechanism in regular magnets. He saw this as necessary to account for the part of his explanation that states that certain particles react only with certain other particles:

Robert: I could probably ask more about this thing.

Ms. S.: Like what?

Robert: Like how these from this side would get over to this side without.... Like, how would this one know to go to this one. That would be a question. And I would probably answer it by saying that the two things that are in there aren't attracted to each other. They're like a magnet. I'd say that. And then people would probably ask me what would happen to the other oxygens. What would they do? And uh, then I would say that the baking soda.... There's three oxygens, so it's a different thing. It's an ozone. That's separate from these two separate oxygens and this separate carbon. I could argue that by saying that. And I think that I could probably think of a few more things, but I.... Yeah, that's about it.

Ms. S.: So you're saying it's like a magnet now. Right?

Robert: Yeah. The ones that kind of.... But it's more like.... It's like there's one side there and the other side there, and those two attract, and the other two repel. This is like an extended magnet. This one attracts with this one, and this is maybe your N side, and this is your S side, and maybe this an L side, and this is an M side, so then it will.... So there's lots of things that attract and repel each other.

Ms. S.: So, it's not just north and south. There's all kinds of different forces?

Robert: Yeah.

Ms. S.: And how come you need all kinds of different forces?

Robert: So that this will link with this one here. They need forces, so they will all be different things when they're finished. Like I could just get a chain of them all here. Like north and south, and they'll move around, and they're together here and so on down the line. So I need different forces so that one

> doesn't go on to all the elements. (Chemistry Interview, May 29)

Here, Robert identified the possibility of a new force. To develop his idea, he could have continued to evaluate it by means of analogy, or he could have tried to think of predictive implications to test his idea. The level of complexity that his explanation had reached could have made this difficult, but it is important not to underestimate the creativity and ingenuity of students at this age.

According to Clement (1989b),

> In this process [that of "successive refinement"], it does not matter so much if one makes a faulty conjecture; it may still be possible to transform it into a successful conjecture by carrying out a series of criticisms and modifications. (p. 372)

Robert's development of his analogy demonstrates one stage in the process of successive refinement. His ability to question himself also displays evidence of one of the characteristics that Clement (1989b) selected to explain the productive theory-generation of the experts in his study:

> There is a willingness in S2 to criticize vigorously and attack the validity of his own conjectures. He is able to engage in dialectic conversation with himself, proposing new ideas on the one hand and criticizing them on the other. (Clement, 1989b, p. 375)

These ideas are applicable in areas beyond evaluating the applicability of analogies, but seem very important within this context as well.

#### 4.3.2.4. Level 4: Systematic evaluation of analogy: Breaking free from binding paradigms.

Acquiring strategies and habits of mind for carefully evaluating the analogies that our minds naturally form is clearly important for effective analogical reasoning. Level 4 AR is achieved with the awareness of the manner in which analogy necessarily binds human reasoning, often in ways of which we are not consciously aware. This understanding may be viewed as a logical extension of the development of and reflection upon the mapping and verification strategies that define Levels 2 and 3 AR. Once students attain this understanding, they may become more aware of traps that constrain their thinking in unproductive ways and thereby be more consciously able to break free of binding ideas. This was evident in the work of some of Clement's (1989b) experts.

Finding ways to generate more or better analogies may be less straightforward. If analogy-generation is rooted in the nature of the knowledge structures which comprise the mind, perhaps conscious attention to the types of thinking that facilitate the growth of integrated knowledge structures is the only way to achieve this goal. Whether conscious attention to mapping the strengths and weaknesses of already existing analogies eventually leads to greater facility in generating analogy remains to be seen. This is discussed in greater detail in Appendix I.1.

Spiro et al. (1989) identified "analogy-induced misconception" (p. 502) as a critical barrier to effective understanding and identified specific ways that the faulty interpretation of analog relationships may negatively influence reasoning. However, the strategies they suggested for helping students deal with these pitfalls were primarily didactic. Helping students to analyze their own analogies in a manner that allows them to recognize the ways in which analogies may break down displays much more respect for the ability of children to become independent learners. If seeking ways to avoid the misleading tendencies of certain analogs is viewed as the primary responsibility of the teacher, the child's ability to generate and evaluate his or her own ideas is not encouraged or developed.

Spiro et al. (1989) described "analogy-induced misconception" as follows:

> All of the examples have two features in common (a) The source (or base) domain information in the analogy is inadequate or potentially misleading for understanding the target domain (the topic); and (b) in practice, the knowledge acquired about the topic is reduced to just that information mapped by (inadequate) analogy from the source domain. This includes both incorrect *overextensions* from the source (derived from misleading aspects) and *omissions* in the source of information important for understanding the topic. (p. 503)

The authors did not claim that these only occur due to implicit analogies, but, if they were implicit, certainly their effects on thinking would go unnoticed and unchallenged. The ability to consciously seek and articulate the implicit factors guiding one's thoughts defines Level 4 AR, and may have important implications for education.

Examples of students making conscious attempts to escape a restrictive view of thinking were not observed in the data collected during this study. It seems that this may be a more advanced skill that requires a high degree of metacognitive awareness of the analogy-mapping and validation processes. One of Clement's (1989b) subjects demonstrated a conscious attempt to free himself from the paradigm that he felt must be restricting his thinking. Many portions of this subject's protocol demonstrate his discomfort with the analogical relationship that was guiding his thinking as he took part in the study. This discomfort eventually prompted him to make the following comment:

> I feel as though I'm reasoning in circles. I think I'll make a deliberate effort to break out of the circle somehow. What else could I use that stretches...like rubber bands...what else stretches...molecules, polyesters, car springs [leaf springs]...what about a ... two-dimensional spiral [watch] spring? That doesn't seem to help. (p. 353)

Later, he indicated that he was still having trouble shaking his old way of thinking:

> I keep circling back to these same issues without getting anywhere with them.... I need to...think about it in some radically different way, somehow. Let me just generate ideas about circularity. What could the

> circularity [in contrast to the rod] do? Why should it matter? How would it change the way the force is transmitted from increment to increment of the spring? Aha! Now let me think about; Aha! Now this interesting. I imagined; I recalled my idea of the square spring and the square is sort of like a circle and I wonder...what if I start with a rod and bend it once (places hands at each end of rod in Figure 8 and motions as if bending a wire) and then I bend it again? (p. 354)

He explored the new analogy and indeed found it more productive. Clearly, he made very conscious efforts to break free from a restrictive way of thinking.

Thinking in this manner is clearly not an easy task. We think with our theories, and if our theories are rooted in a certain model, it is very difficult to consider alternatives. Clement (1989b) made the following comment regarding the subject described above:

> ... S2 finds it very difficult to give up the bending rod model. The persistence of this model appears to be an example of an Einstellung effect; a problem space dominates his thinking and prevents him from generating necessary new ideas. In order to make progress, S2 must redescribe the problem using new descriptors; he needs a new problem representation. But the rod model keeps reappearing in the transcript. Even though he proposes rejecting the model several times, he is repeatedly tempted to return to it. It is as if the idea has an autonomous "life of its own." (pp. 370-371)

Despite the difficulty in shedding unproductive thought patterns, it is not only scientists who need to undertake the challenge. As I attempted to develop my own understanding of a wet cell, I realized that something had to be wrong with the way I was thinking. My mental model simply was not allowing me to develop a consistent and workable explanation of the battery. I did not see any obvious flaws in my reasoning, but it did occur to me that there was some kind of conflict between my attempts to view the flow of electrons in a circular path and the implications of the logical step-by-step approach that I was using to try to piece together a more coherent understanding of the whole system. At this point, I realized that my implicit view of the battery as part of a simple DC circuit was constraining the way I was thinking:

> On my way to work on Friday, I was again trying to visualize the manner in which electrons are forced around a circuit. To do this, I needed to understand how it is that the electric potential in a dry cell is created. I had looked this up in a book and found an example of a wet cell with copper and zinc electrodes in a sulfuric acid electrolyte. As I was attempting to picture the electron path through the entire system, I finally realized that the electrons in the wire do not travel in a "circle" which includes the electrons in solution. I had been envisioning the whole system as a circle. This was likely the result of models such as the train [an analogy for electron travel used to show that all move together] and the very manner in which circuit diagrams are drawn. Electrons travel from the zinc to the copper electrode, but do not travel from the copper electrode back to the zinc one. They combine with hydrogen and escape as a gas. (Research Diary, December 8)

This was only the first step, however, as the circle concept was at the base of the whole way I was thinking about the problem. I had to rethink many aspects of the problem while tracing the path of the electrons throughout the battery and trying to build a new holistic image in my mind.

Some of the students' reasoning about their battery models also suggests that viewing the flow of electrons in a circular path may have restricted their reasoning about the battery to a certain range of possibilities:

> Samantha: Yeah. It's got to go back into the battery, 'cause if I only had one half, well then, just, it doesn't really make sense to me, because like, actual batteries have two halves. Like they have -
>
> Ms. S.: Do they have a divider?
>
> Samantha: Um.... I think so. I'm not sure.
>
> Ms. S.: How about the wet cell or the lemon?
>
> Samantha: Well, the lemon, um.... If you just have, like, two acids mixing and going around and around [motioning on her

diagram], coming out, and going back in, around and around and around, wouldn't that make a short circuit?

Ms. S.: What do you think?

Samantha: I think it would. I think the battery would get hot after a while.

Ms. S.: Because the stuff is mixing in here [pointing to Samantha's diagram]?

Samantha: Like, if you have a wire going out the top of your battery, and there's your light bulb, and the wire going back in, unless.... You could.... I guess you could have two acids mixing, but they would have to be, like, two different acids. Like, they couldn't be attracted to each other. Like, they couldn't mix, 'cause they.... Maybe they're in separate.... Maybe each little particle is in its own little bubble sort of like, and there were five bubbles of one kind and five bubbles of a different kind or something, and then they might be able to be mixing, and some would go out and some would be the old ones. (Battery Interview, March 30)

At this point, Samantha continued to develop the bubble analogy introduced in Section 4.3.2.2.3. In this model, the particles do not continue to circle and are able to return to the battery in a different form. Although her model leaves many questions unanswered, Samantha is moving toward a model that is increasingly consistent with the observed effects of batteries and certainly contains some accurate elements.

Whether Grade Five and Six students can be guided to the level of self-understanding required to undertake a more systematic evaluation of the implicit analogs that may restrict their thinking remains to be seen. In any case, helping them move in this direction seems an important goal. As they are encouraged to identify implicit models to more clearly communicate their ideas to others, to consider the transferability of explanatory structure between potential analogs, and to reflect upon these processes, they may begin to realize pervasive manner in which analogy guides their thinking.

### 4.3.3. Implications-based evaluation (IE).

This section focuses on the evaluation of theories by means of considering their power in explaining familiar events. As students progress through the levels developed here, they move from Level 1 IE considerations of discrete components of phenomena in question to more cohesive accounts of those phenomena at Level 2 and eventually toward the identification of observable implications at Level 3 and alternate implications at Level 4. There is considerable overlap between this and both the FOI and AR frameworks, but unique elements are also present. For example, theories based on analog models may be evaluated through the formulation of testable implications, and implications may in turn be identified by analogy. The focus here, however, is on identifying and manipulating the parts of selected phenomena to develop plausible explanations of the manner in which they behave. In many ways, this is the inverse of analogical reasoning, in which explanations begin with a broad structure against which the components are evaluated. Even so, salient components may be identified by means of analog models. Clearly, the separation of the AR and IE frameworks is far from complete. Students continually move back and forth between the three frameworks and use components of one within the other. However, considering them separately is useful in analyzing the components of reasoning unique to each.

When piecing together components identified as salient, students essentially need to find out how they can manipulate the pieces in a manner that produces the desired output. Typically, there are many (if not infinite) ways in which this may be done. Evaluatory measures typical of Level 3 FOI (WWTH / SWIID) help to narrow these possibilities, but even with these constraints, many explanations are possible. Clement (1994) noted that imagistic simulations are often accompanied by predictions. The students in my study often imagined their explanations in action, but often their models were somewhat fantastic creations for which they had difficulty identifying, or even understanding the need to identify, testable implications. The IE framework's focus on the development of broad explanatory power represents a further attempt to consider the rationality of proposed explanations.

#### 4.3.3.1. Level 1: Isolated-case reasoning and accidental implications.

Students at Level 1 IE do not make conscious attempts to integrate related arguments or phenomena. Components are mentally placed together in a manner that explains the part of a phenomenon being considered at a given moment. Explanations regarding other facets of that phenomenon may or may not be consistent with one another, but it seems likely that students at this level are unaware of this inconsistency. They do not systematically collate or juxtapose different aspects of their explanations and therefore often fail to recognize inconsistencies that are quickly apparent to them when someone else asks, "How does that fit with…?". The absence at Level 1 IE of the observed tendency of students at Level 2 IE to perform mental replays of explanations once they have been formed may help to explain these students' non- perception of discrepancy. Modifications and extensions are made to theories as the students piece together their ideas, but only if imagined implications directly challenge well-established expectations. These implications are expectations based upon the manner in which imagined components should interact. The students do not generate them deliberately to test their ideas.

When identifying a line of reasoning as isolated, it is important to distinguish between a failure to consider ideas in a manner that would make discrepancy obvious and a failure to see a relationship that may appear obvious from the outside. If students do not see situations as analogous, of course they will not see the need to develop explanatory structures consistent with those phenomena. To ask oneself, "How does that explain...?" requires the identification of situations that it should explain. In this context, the presence of well-integrated knowledge structures emerges as a critical feature in the identification of situations that should be explicable with a given theory. If a student is unable to identify situations such as these, this may be more an indication of the state of his or her knowledge base than it is of a general tendency to base reasoning on isolated cases.

Level 2 FOI may indirectly promote apparent isolated-case reasoning of this nature. As the students were proposing various circuit arrangements that could be tested as possible solutions to the problem of having a burglar alarm go off simultaneously in several rooms of a house, Frank offered many suggestions for ways to hook up the circuits. However, none of these were explicitly connected to a broader theory that would be supported or refuted by their observed effects (see "Frank (A)" - "Frank (D)" in Appendix D.2). That he does not connect his ideas to a broader theory may contribute to the development of non-integrated knowledge structures, which could in turn help to explain the lack of perceived connections between various phenomena. This differs from failing to search deliberately for other situations that a given theory should explain and from failing to seek consistency among new and previously developed arguments. It appears to be an issue of perception rather than one of motivation or of poor metacognitive understanding regarding the need to ensure a theory explains all relevant phenomena.

There are some instances in which students failed to consider how their explanations would apply even in situations that they did see as analogous. Part of the difficulty here may lie in an inability to consider multiple situations simultaneously. This could be based on problems with short-term memory, an inability and / or non-tendency to reduce knowledge to components that can be processed simultaneously in short-term memory, and / or a failure to perceive the need to seek out situations that should be explicable by a given theory. The first two points are discussed in greater detail in Appendix I.1, whereas the last one is the primary focus of this section.

As the days progressed during the electricity unit, all of the students more systematically tested their ideas against a variety of circuit arrangements. However, in many cases, this was only after the importance of explaining those particular circuits was made evident during class discussions during which their ideas were challenged on this basis (e.g. "How would that explain an $x$ circuit?"). In itself, this does not represent a generalized understanding of the need to seek ways of explaining related phenomena.

Frank had particular difficulty generating theories that could be consistently applied. Part of this difficulty may have been rooted in his vague understandings of his own theories and in the fact that he typically did not engage in the mental replays that helped some of the other students create more simplified and cohesive images of their models. The following comment portrays one of Frank's early attempts to use his crashing-current theory (whereby energy from the positive and negative sides of a battery crash in a bulb to create heat and light) to account for the behavior of two bulbs in series. This was a persistent difficulty, as is shown in the examples that follow:

> Frank: Yeah. And then there will be a light bulb here, and there will be another light bulb here [in series], and then there'll be wire

> like that [in between the two bulbs]. And the same thing will happen. Energy will come up like this.... It'll go up, and this time, though, it'll go up into the bulb, and they'll go around, and it'll come, and it'll pass each other in this wire at the same time. (Class Discussion, March 11)

For energy to crash in both bulbs, some has to get through the first bulb and into the second so that there is something to crash with the energy coming from the other direction. But if some of the energy can get by, why doesn't all of it? It is possible, of course, that the visual image in Frank's mind does provide a mechanism that allows this to occur. For example, if viewed in the manner of colliding galaxies whereby the large distances between stars allow the galaxies to pass through one another with few or no star collisions, most of the energy pieces in a circuit could pass through without crashing. The thin filament in the bulb could lead to a greater number of crashes in the bulb than occurs in the regular wire. Frank does not articulate this idea or any other that might explain why the particles don't all crash. Perhaps it is so clear in his own mind that he does not see the need to articulate his views on this matter, but this seems unlikely in light of other examples that provide further evidence suggesting that his reasoning is often limited to isolated cases.

In the next example, Robert expresses concern with the idea that positive or negative energy could be left in wire after it has been disconnected from a battery. According to Frank, it is essential that the wire always be full of energy so that each time a circuit is reconnected, new energy from the battery is able to push against energy already in the wire and cause the bulb to light instantly. Despite my suggestion that even new wire could be full of marbles (a concrete analog we used to envision particles in the wire), Frank avoided Robert's concern by claiming that he was talking about used wire.

He had almost certainly used new wire in his own investigations, however, so skirting the issue was not an acceptable solution to this problem:

| | |
|---|---|
| Robert: | It should move. But then if you got a new piece of wire, and there's no marbles in there, then it's not going to move. |
| Ms. S.: | Unless wire is full of marbles all the time. |
| Frank: | Because maybe it's used wire. (Class Discussion, March 16) |

Frank's subsequent attempts to deal with the dilemma of positive and negative wires continued to focus on the single instance being questioned, and he failed to anticipate other possibilities that rely on the same principle. Switching the hypothesized positive and negative wires still allows for crashing, but does not account for what would happen with two positive wires or two wires of different length. In the end, he tried to reconcile the difficulty by suggesting that something goes through the wire and changes all energy to the needed type:

| | |
|---|---|
| Andrea: | Frank? |
| Frank: | Okay. For this one, mine, Keith said, "What if you switched these two?" Right Jennifer? He said, "What if you switch these two wires [the positive wire and the negative wire]?" |
| Jennifer: | Yeah. |
| Frank: | Maybe since you switched them, it would still work, because they'd use up these ones, right? And since the new ones keep on coming at the same time, they would come down, and they would start being used, because they are both mixing still. |
| Ms. S.: | But you said you had to have both positive and negative to mix, right? |
| Frank: | Yeah. So, if you switch this. This is now a positive, and this is now a negative – |

Ms. S.: But would that always be -

Frank: And all the ones that were here would get used, and then the ones that were coming out of here, this would turn negative and this would turn positive.

Ms. S.: Okay, but Frank, how do you know.... If you just grab two wires out of a drawer, how do you know that one is positive and one is negative? How do you know that you're not grabbing two positive wires?

Andrea: You don't know.

Frank: Maybe there's like, something that comes through and changes them. And I've got another one. And for Keith's, not tunnels, friction. When me and Robert have to sit together on the bus, right? And we told Amy to.... Let's say this is the bus seat. We told her to keep on hitting her fist on the seat, and her fingers got all black, and the nails got all black. (Class Discussion, March 16)

It is possible that Frank would have considered two positive wires on his own had I not challenged his idea so quickly, but the same dilemma reappeared in his individual interview a few days later. At this point, he again invoked the idea of a scanner that could go through and convert positives to negatives or vice versa.

Frank's use of different explanations for similar phenomena is also evident in his inconsistent use of tunnels to explain various circuit phenomena. Wire with separate tunnels for positive and negative energy had been suggested as a means of separating different energy types to prevent them from crashing in the wire connecting two or more bulbs connected in series. Early in his battery interview, Frank explicitly articulated his discomfort with the existence of tunnels in wire. Later in the interview when I asked him to consider how a one-way circuit might work, he again used them to explain away difficulties posed by two bulbs connected in series. The spiraling theory that he generated at the end of the interview represents an attempt to resolve both issues, but, as was the case when he invented the scanner, he only attempted this after his ideas were directly challenged:

| | |
|---|---|
| Frank: | Yeah. So, right now, the energy is coming from that side [of the battery], and it'll.... It comes to this light bulb, and it'll go up there through those wires. It'll go through there, and it'll come back out and go down [through the first bulb]. And then it comes across here [through the second bulb], and then, at the same time, the same thing is happening [from the other direction]. I think there's two little tunnels inside, right? Actually, I don't like the tunnel idea, but.... |
| Ms. S.: | How come? |
| Frank: | Well, because sometimes I do. |
| Ms. S.: | How do you think about the tunnels? Good and bad. |
| Frank: | Well, I think that it's good, because then you can...because then the energy could pass there. In the middle [between two bulbs connected in series]. But it doesn't really make sense. 'Cause people made wires, right? Why did they.... Why would they put holes in them? How could they put that small of a hole in them? |
| Ms. S.: | Okay. So, it just doesn't seem like a logical thing to have those tunnels? |
| Frank: | Yeah. So instead of that, I think they'll just move to the side and pass each other. (Battery Interview, March 16) |

Later in the interview, tunnels became a convenient way to explain a perceived discrepancy in a one-way circuit:

| | |
|---|---|
| Frank: | Maybe instead of this idea here.... Maybe in Andrea's theory [a one-way model], instead of this wire going this way, there'd be a big end there, and it won't have nowhere else to go, so it would crash there and light. 'Cause it wouldn't have nowhere else to go, so – |
| Ms. S.: | Oh, okay, but do you remember.... Do you mean put a wall in it again? Like in your bulbs, she talked about putting a wall in it [a divider in the middle of the bulb to separate the |

two kinds of charge]? And there's nowhere to go, so they crash? Okay, but then what happens here? Remember, she had the problem of what happens when you have two of them, then? Like, if they crash here, how are any of these going to get over here [past the wall to a second bulb connected in series]? They can't get past this wall. How are you going to get any of this over to here to light that bulb?

Frank: Maybe there's a.... When you hook up the wire, right? Okay, yeah, when you hook up the wire, and that comes back to the tunnel thing we had before. She has the tunnel thing, and it would be coming like this -

Ms. S.: Okay, but do you like the tunnel thing?

Frank: Well, for some things and some things not.

Ms. S.: Like, try to put together pieces that you do like.

Frank: For this one, I would like this way. For this one -

Ms. S.: But, you said you didn't know how to make tunnels. You said tunnels didn't make sense, because how could we make them?

Frank: Yeah, so....

Ms. S.: Do you know what I mean? So if you can't make the tunnels -

Frank: Okay! So like on the alligator clip, they'd be spiraling, right? And then they'd go up in here, and they'd be going straight. Then they'd hit the wall, right? Maybe, on the wall, there's a wire going down here, and it goes like that, right? And there's another wire, and they meet, and it goes like that, and then it can go through to the other bulb [drawing on his sheet of paper]. And the same thing with this. (Battery Interview, March 16)

On his own, Frank considered only a single-bulb circuit for both his clashing-current model and for the one-way current model that I asked him to consider. When I asked him to consider two-bulb circuits with the one-way current model, he modified his ideas accordingly. He expended considerable effort explaining the manner in which the bulb could use half of the energy at a time. Apparently, however, the possibility of a third bulb still had not occurred to him:

> Frank: And it crashes there, too, and then there's nothing left after it crashes two times.
>
> ...
>
> Frank: Yeah. And it'll go like that, and this one will crash, and half of that will be gone now, so that half is gone. Well, this half is gone, and this half is used, right? And that's the same thing with all of these. And that'll go down to that one, and the other half will get used of the energy, right? And then it'll go around and go back into the battery, and then it has nothing. (Battery Interview, March 16)

Frank's isolated-case approach to evaluating his battery is even more evident when juxtaposed with the systematic attempts that other students made to test their models against a wide variety of actual situations. These are presented in the next section.

#### 4.3.3.2. Level 2: Broad explanatory power.

> *The question is, of course, is it going to be possible to amalgamate everything, and merely discover that this world represents different aspects of one thing? Nobody knows. All we know is that as we go along, we find that we can amalgamate pieces, and then we find some pieces that do not fit, and we keep trying to put the jigsaw puzzle together. Whether there are a finite number of pieces, and whether there is even a border to the puzzle, is of course unknown.*
>
> (Feynman, 1995, pp. 26-27)

Like students at Level 1 IE, students at Level 2 formulate explanations by piecing together known components in a manner that is consistent with known results. However, at this level, they make deliberate attempts to maintain consistency among a wider range of phenomena.

After identifying and rationalizing components of the vinegar and baking soda reaction believed to be salient, students at Level 2 IE pieced together their understandings of how the reaction might proceed. Throughout the examples provided, additions and modifications to theories are common occurrences as the students attempt to develop mental images that were visually plausible and consistent with previous arguments. In the following dialogue, Carl summarized a theory that he developed prior to the conversation, and Keith clarified his emerging views by mentally (and on paper) arranging and rearranging the particles he hypothesized as salient. As he did so, he attempted to explain a variety of phenomena that he believed his explanation should account for (i.e. the formation of a gas, certain properties of that gas, and the formation of new substances in the petri dish):

Carl: Are you going to share first or should I?

Keith: You should.

Carl: Okay. I think that when vinegar, $CH_3COOH$, that's the chemical compound of it, and baking soda, $NaHCO_3$, meet, the $CH_3COOH$ -

Keith: That's vinegar.

Carl: Takes one oxygen from the baking soda, $NaHCO_3$, making the formula $NaHCO_2$. Then the $CO_2$ separates from the NaH. That's why we get the $CO_2$ gas.

Keith: You should talk in more normal sense.

Carl: It's kind of hard.

Keith: Draw a diagram.

Carl: And, um, the NaH combines with what's left of the $CH_3COOH$, making something new.

Keith: So which is the gas?

Carl: The gas?

Keith: $NaHCO_2$?

Carl: Okay, look. This is what happens. This is vinegar and this is baking soda [showing Keith on sheet]. When it's added, this is the baking soda and this is the vinegar, and they meet. And it takes one oxygen, probably making this COOO or something like that.

Keith: No, I believe that the carbonate.... It's vinegar that reacts, which attracts the carbonate.

Carl: Possibly. And then I have the questions: "How does it take the oxygen?" And that I can't answer yet. And, um, "What is the formula for the new substance - the NaH + $CH_3COOH$?". I don't know what that is, though.

Keith: That's vinegar!

Carl: No, I don't the formula for when they make this. I don't know what the formula is, the chemical compound.

Keith: It's simple! All you have to do is -

Carl: [laughing]

Keith: [laughing] Well it is! So I've made up these diagrams of what vinegar and baking soda are, and I think, uh.... Pretend this is eight molecules and that's six.

Carl: Atoms.

Keith: Atoms, I mean. One molecule, eight atoms to make up this vinegar. So when they meet, there's carbonate. Which would be the carbonate?

Carl: The C.

Keith: Oh, yeah. Um, I have to check back. Carbonate is $CO_3$. Okay, so the carbonate, $CO_3$, reacts with the baking soda.

Carl: The $CO_3$ is the baking soda.

Keith: No it isn't.

Carl: The $CO_3$ is in the baking soda.

Keith: That's carbonate.

Carl: The $CO_3$ is.

Keith: Yeah. So the $CO_3$ from the baking soda reacts with.... All I have to figure out is what is acidic [acetic] acid in a molecule.

Carl: Well Keith, you got the formulas wrong. It's supposed be NaHCO.

Keith: It doesn't matter.

Carl: Yes it does.

Keith: No it doesn't.

Carl: Because if it's small, then it's something else.

Keith: I just put it there.

Carl: Okay.

Keith: Well, when that reacts with it. Pretend, uh, that's $CO_3$ there. That reacts with the acidic acid. Oh yeah! What is acidic acid? Acidic acid is $C_2H_3O_2$. Is that the kind we're using?

Carl: Acidic acids? No.

Keith: Is that what's in vinegar?

Carl: No.

Keith: I'd think so.

Carl: Well, H is made up of $C_2H_3O_2$.

Keith: No.

Carl: Yeah.

Keith: That's H. That's H. It's hydrogen.

Carl: And that's what it's made up of.

Keith: No. Acidic acid is $HC_2H_3O_2$. Wouldn't it be?

Carl: Yeah. I guess.

Keith: Okay. Uh, so it's $C_2$, so it takes the two carbons, takes the three hydrogens, and two O's. So all that's left is hydrogen with vinegar. So hydrogen.... What is hydrogen?

Carl: It's a gas.

Keith: Is it lighter than air?

Carl: Yeah, helium and hydrogen both are. Hydrogen is flammable, though.

Keith: Okay. Then that and Na.... So the sodium and the other hydrogen.... So this would be [working on paper].... Here's the Na, the H from the vinegar, the leftover H from the baking soda, and that's the new gas. Cool! I never figured that out before.

Carl: Now we're finished.

Keith: Yeah, I'd say so. (Discussion between Keith and Carl, May 11)

Following their discussion, I showed Keith and Carl several gas tests, and they were able to identify the gas produced in the vinegar and baking soda reaction as carbon dioxide. The results of these tests supported Carl's theory, but left unanswered his question regarding why the particles would break apart and recombine in the manner he suggested.

By Level 2 IE, students have developed self-questioning skills that directly pertain to the explanatory power of the theories they are developing. The ability to search systematically for phenomena that should be explainable with a given theory is an important descriptor of activity at this level. For example, it could be argued that a good battery explanation should explain the results of different battery arrangements, different bulb arrangements, short circuits, and the difference between conductors and insulators. All of the students readily accepted the need to explain different bulb and battery arrangements with the same battery model, although their initial attempts seldom considered all of these features. Arguments such as, "How does that explain an *x* style circuit?" were used consistently during class, however, and eventually all of the students began to incorporate these types of questions into their own self-questioning. In itself, this could have been a context-specific understanding rather than a more generalized understanding of the need to seek out independently situations that a given theory should explain.

Frank, who demonstrated the tendency toward isolated-case reasoning profiled in Section 4.3.3.1, spontaneously considered at least two circuit arrangements as he explained his battery to the class:

Frank: Okay. Anybody else? Okay. If nobody has anything else, I'll do the two-one now.

Jordan: The what?

Frank: [drawing on board] The two bulbs. This is quite the same.

Jordan: Two bulbs or two batteries?

Carl: Two bulbs.

Frank: Mine's sort of like Rebecca's style.

Robert: Then you can't do a different style than Rebecca's.

Carl: Well, it's sort of like Rebecca's.

Frank: Yeah, it's sort of like Rebecca's.

Ms. S.: He's not saying it only works for Rebecca-style. He's saying the example he's using is Rebecca-style.

Frank: See, it's the same thing, only there's only one bulb.

Ms. S.: So, you've already explained Samantha-style is what you're saying? (Class Discussion, March 11)

Frank's consideration of both types of circuits was likely a response to his growing awareness that his battery model would be questioned on these grounds. By contrast, Robert's contributions to this dialogue suggest a very clear understanding of the need for an explanation to work in a variety of different circumstances.

From the beginning of our discussions, Robert demonstrated exceptional skill with regard to seeking wide-ranging phenomena that a theory should explain. He generated many of the initial arguments that other students used to continue evaluating their own models. Although he did not immediately articulate his understanding of the need to identify these situations deliberately, his approach did appear very systematic. Typical comments follow:

Robert: Okay, for Samantha [using her diagram on blackboard]. How would you get acid leaks? It sounds so covered, you couldn't get acid leaks in any way, pretty much from what it sounds. The acid couldn't get out through the metal or through the sides, and then she said that the acid was quite loose, so then, could we hear it? And then how would we get a hot wire, and is this a different acid than this to make electricity? (Class Discussion, January 14)

...

Robert: Now, for Jordan's. How would we get power from acid, and on this one, are there two different acids? And if there's a wire through here, and these two are mixing to make power, then would there be power all the time? And this end is connected to this end, so it would hot wire. And then how would you get different amounts of volts? And how would it work with a square battery? (Class Discussion, January 14)

Keith showed a great deal of growth in his ability to consider a variety of situations for explanation. At the end of his second battery interview (Keith was interviewed both at the beginning and the end of the electricity unit), he made the following statement, indicating his awareness of the importance of considering his battery model in the context of a variety of familiar circuit applications:

| | |
|---|---|
| Ms. S.: | Okay. Anything else? Like, what about your own self - How do you get your ideas and your questions? |
| Keith: | How come this works, how come that works? (Battery Interview, April 1) |

One characteristic of student argument that seemed to help some students extend the explanatory power of their models was the tendency to consider quantitative variations of a particular phenomenon. For example, a good model should explain a circuit with any number of bulbs or batteries. This typically involved extension to one or more other cases (e.g. two bulbs or two batteries). In rare cases, a student would attempt to extend the model to extreme cases:

| | |
|---|---|
| Ms. S.: | And so now if you put another bulb in here, does it still work? |
| Carl: | Uh, how can I make this work? Um, well maybe a bulb only uses a little bit of the energy that's going through and a little bit of good stuff that's coming back in. In through here and then into there again. And it gets used again. So maybe it only uses half of the needed energy, or half of the put-through energy, or one third, or one billionth or whatever. And then this one uses another billionth or whatever, and then the next one uses another billionth until they have a billion light bulbs and then they don't light each other anymore. |
| Ms. S.: | Okay. |
| Carl: | And then they don't light. (Battery Interview, March 25) |

The use of this strategy seems to involve a generalized understanding that the process of extension could go on ad infinitum: Simply explaining a one-bulb or two-bulb circuit may not fully cover the necessary range. By considering an extreme, the need to consider a great many possibilities in between may be eliminated. This strategy is particularly useful when contrasted with the isolated-case strategies presented in Section 4.3.3.1.

#### 4.3.3.2.1. Instant replay.

After mentally piecing together salient components to form complex ideas, some students mentally replayed their ideas from start to finish. This seems to be a very useful strategy for clarifying the broader picture or explanation that they are attempting to develop. As explanations are pieced together, there are typically many changes that interrupt the flow of thought. Putting all of the pieces back together at various points during the generative process seems to allow explanations to be considered in a more coherent manner that allows consideration of the explanation in its in entirety and therefore better highlights inconsistencies inherent within it. The following summaries condense a lengthy series of theoretical developments that were made in response to perceived difficulties in explaining how current could crash in multiple bulbs that are connected in series:

> Robert: Let's see how I did this [drawing].... There. OK. Then you've got your positive, and it's going through here, and then you've got your negative, and it goes in here, and lights this, and then the negative through here doesn't have as much force as the positive, so the positive from this side is weak, because it has been through here. So it's only half the size it was before. So then the negative is stronger than that positive, so they go past each other, and then.... (Battery Interview, March 26)
>
> ...
>
> Robert: So it's weaker, and then this will pass by here, and then, so you don't get a hot wire, the plus doesn't...is not pushing as much

> anymore, because it's weaker from being used up. So then they can get by and through each other. (Battery Interview, March 26)

The smooth flow of ideas evident in these summaries provides a notable contrast to the convoluted nature of the initial development of these ideas.

After Frank had developed a rather lengthy and complex explanation regarding how the negative and positive pieces could still crash if there were positive pieces in both wires (leftover charge from the last time the wire was used), I asked him if he could think of a way to question himself. A better prompt may have been, "Could you replay your idea from start to finish?" In this manner, discrepancies and gaps of which he was unaware may have been made apparent. Later in Frank's interview, I did request that he summarize his theory, but only because I did not realize that he had already explained his point. I was confused about how his battery was supposed to work. In reiterating, Frank initially had considerable difficulty in some areas, but eventually restated the theory almost exactly as he had before. If restating the theory was as difficult as it appeared to be, it is little wonder that he was often unable to relate his ideas to other situations and sometimes seemed to apply his ideas inconsistently. If he were unsure about how his original model worked, it would have been very difficult for him to consider how it might work with a different circuit arrangement and would therefore make the illumination of situations that were discrepant with the poorly understood theory highly unlikely.

#### 4.3.3.2.2. Recognizing ad hoc tendencies.

> *When I found out that Santa Claus wasn't real, I wasn't upset; rather, I was relieved that there was a much simpler phenomenon to explain how so many children all over the world got presents on the same night! The story had been getting pretty complicated – it was getting out of hand.*
>
> (Feynman, 1988, p. 26)

As the students used identified components to build explanations consistent with observable outcomes, it soon became apparent that there is almost always a way to manipulate the pieces so that they come out the way that you want them to. Several of the students recognized this and made reference to it in both the context of classroom arguments and during their personal interviews. Most of the time, this took the form of reference to the idea that simpler ideas are better than those that require very complex explanations. This concern was largely a product of the difficulties the students had in justifying such arguments to the critical audience that their classmates comprised, but it was often this very difficulty that made evident the weaknesses inherent within them.

Robert's discomfort with a lengthy explanation that he developed to explain how energy could get through a bulb without being used up so that there would be some left to light a second bulb connected in series provides evidence of his concern with ad hoc hypotheses:

Robert: Yes. So then the bad stuff is on both sides here, so it's stopped. It's not letting any good stuff in, and then.... This isn't working right. Oh how does this work? [thinking] Maybe the bad stuff goes through here, and hits this wire, and then it sends like a shock through the wire, a zap through the wire, and then it zaps this, and then it's zapping, so then half of the energy goes through, because this is being zapped, it's paralyzed on one side. Then -

Ms. S.: It can go through the -

Robert: It can go through the other side, and then it wouldn't be affected. And then it could go through and into here.

Ms. S.: But doesn't it still have to go through the small tunnel?

Robert: Yeah, but just now the tunnel is smaller, because one side is paralyzed.... It's stopped. So this side is taking energy, and it can't take as much, because half of the stuff is taking it out is gone, then it can only take half the stuff out, so then you've still got half the energy coming through, and then in through here.

Ms. S.: So somehow, these got through without giving up their energy?

Robert: Yeah, because the thing that takes the energy....

Ms. S.: So what do you mean by "the thing that takes the energy"?

Robert: Uh, energy sucker thing, I guess!

Ms. S.: Well, where is the energy going?

Robert: Into the wire, so that basically, the wire is.... Half of it can't take the energy, because half of it's being zapped, so then the energy has to squish through the whole wire. But only half of it is getting hot, because the other half is being zapped. So then it goes through, and the half that isn't zapped goes through and into here, and then it's stopped.

Ms. S.: Do you have questions for yourself on that one? What do you think of that?

Robert: That's why I don't like this one.

Ms. S.: So you don't particularly like this explanation?

Robert: No.

Ms. S.: How come?

Robert: Just because of this. It's hard to explain, and I don't see how the acid or energy can turn hard if it's not there, almost. That's why I don't really like this one. It's like right here it's turning hard, because it's bad.

Ms. S.: And bad energy turns hard right away?

Robert: Yeah. That's pretty much what it sounds like. It's like the bad energy is, yeah...harder.

Ms. S.: So, right now then, if you were to pick one, would you prefer this or this?

Robert: This. This one just has quite a few things that are hard to explain, and even when you explain them, they still don't make sense, really. (Battery Interview, March 26)

Samantha's preference for simplicity is evident in the following passage:

Samantha: Well, the one, like, this one [the model she does not like] is kind of like everybody sort of has that idea. Like, it was like my old idea, too. It's just a little bit different, but it's like how the process works is different, but I had a battery like this, and me and Robert had two pages of [written] arguments on it. So... um.... (Battery Interview, March 30)

In these cases, all or part of the students' rationales for wanting simpler arguments may have been that they provided less room for others to disagree with them and made the job of developing consistent explanations easier. However, Robert's comments during the class discussion that focused on developing lists of things that did and did not help class discussion suggest a deeper understanding:

Robert: Well some people, they would have an idea, and they would say their idea and then they had to.... The person would argue it, so they would just make something up off the top of their head and it would be something that wouldn't make sense. So, just saying anything.

Ms. S.: Just saying anything. You mean anything just to save your theory?

Robert: Yeah.

Jordan: It's just nonsense.

Samantha: It doesn't save your theory then.

Robert: It's like you're just trying to chuck something in until you can think of something good enough.

Ms. S.: Okay. How do you want to word that?

Robert: Uh....

Matthew: Chuck something unnecessary.

Robert: Say something that isn't necessary just until you have something necessary.

Ms. S.: Okay. Say something for what purpose? So what exactly.... When is this happening? When is this happening that it's a problem? People are making up things to defend their thing -

Robert: Yeah. They've got a really good idea, so they go up and they tell it, but then the person up there argues it, and then, uh, then they just think of something.

Jordan: Off the top of their head.

Robert: Yeah. They say well this and that, and the person is standing up there...

Jordan: It's just a loss. (Class Discussion, March 20)

As students begin to recognize that ad hoc hypotheses can save just about any theory, they sometimes start to question the credibility of the whole meaning-generating process. This was particularly evident in Carl's work, and his lack of understanding of the need to develop predictive implications exacerbated his difficulties. His emerging belief that ideas cannot be proven frustrated him greatly.

By the end of the unit, he had still not demonstrated an understanding that although they could not be proven, they could be demonstrated as more or less rational than other ideas intended to explain the same concept.

#### 4.3.3.2.3. You can't prove a theory right, so why bother testing it?

As was discussed in reference to Level 4 FOI in Section 4.3.1.4, Carl developed quite a good understanding of the subjective nature of his own ideas, but had not yet transferred this understanding to encompass the broader nature of scientific knowledge. He appeared to be on the verge of Level 4 FOI, but conceptual change regarding his views of the nature of theories and theory-change may be necessary for him to make the final transition. In his chemistry interview, he demonstrated a solid grasp of the relation between theory and evidence, but also displayed strong doubts about his ability to develop rational explanations. These doubts appear to be partially rooted in a lack of faith in his own ability to test important ideas. This is consistent with Moshman and Lukin's (1989) identification of epistemological relativism as a possible stage in the development of metatheoretical understanding:

> Recognition that all data are theory-laden and that apparent falsifications of theory can always be explained away through additional assumptions may lead to epistemological relativism, a transitional phase between Stages 3 and 4 in which the possibility of rationally comparing and testing theories is rejected. (p. 188)

Carl had not yet realized that "all data are theory-laden," but had an apparent difficulty with the implications of being able to explain away the difficulties posed by any given theory. His relativism seemed primarily limited to his own theories. Many of his comments suggest that although he believed that his own knowledge was highly fallible, he continued to attribute higher wisdom to others.

As Carl struggled to explain the vinegar and baking soda reaction at the molecular level, he indicated frustration, claiming that he had a question, but that it was one he couldn't answer: "How does the vinegar take the oxygen?" (Field Notes, May 25). I asked him if he could think of any analogies that might help, but he said that it's like trying to predict how fire would react: "You can't." He went on to explain that he wasn't even sure if the vinegar actually takes an oxygen: "I don't know if this is completely right or completely turned around." He said that it could be either, but that it was most likely wrong, and that there are a zillion ways to explain and a zillion chances of being wrong. It seems that he was terribly frustrated by the thought of investing a great deal of time and effort into investigating a theory that would ultimately turn out to be wrong. Here, he seems to have articulated the beginnings of an understanding of knowledge problematic: "Theories can be on entirely the wrong track, positing incorrect explanations of accurate beliefs and positing entities and causal mechanisms that do not even exist" (p. 52). When I asked Carl how he might resolve his problem, he suggested checking the Internet, because it was the "only way to tell for sure." I reminded him that if he were a scientist doing this for the first time, he would not be able to find the answer on the Internet. I asked him if he remembered a comment that a science fair judge had made to him about proving theories. He did: You can't prove a theory right – only wrong. Rather than demonstrating a clear understanding of the epistemological relevance of the need to falsify theories, however, his comment was likely nothing more than the vocalization of a homily that meant he wasn't allowed to give up. This was also evident in the recurrence of the same issue that evening during his individual interview. Clearly, he had not yet recognized the value of old theories in the development of new. Such a recognition might have helped him to get past his frustration with the ambiguity of his situation. Perhaps further involvement in activities of this nature will allow him to reflect on the development of his ideas in a manner that will allow him to make this realization.

I encouraged Carl to continue developing his idea, and he went into quite a detailed explanation that included fast-moving molecules that he pictured as magnetic marbles in motion. At this point, I don't think he had any confidence in the purpose of doing so. He simply had a good idea and became interested in following it through.

Detailed evidence of Carl's frustration was still very evident during his individual interview that evening, although his apparent antagonism was uncharacteristic and partially due to an irritable mood:

> Carl: Okay, I have a couple questions for myself that I cannot answer. They are: How does it take the oxygen? How does the vinegar take the oxygen from the baking soda to make it $NaHCO_2$? And what is the formula for the new substance? And that I do not know.
>
> Ms. S.: Any ideas?
>
> Carl: Well, I know what's left in the vinegar after it uses what's.... It breaks down the baking soda, so I don't know if anything is used from it or not. So I can't really tell.
>
> Ms. S.: Is there some way you might be able to find out, though?

Carl: Take it to a chemist?

Ms. S.: You are the chemist. How might you find out?

Carl: If I had the right equipment, I could probably find out what was in it. The chemical makeup.

...

Ms. S.: Are there any tests that are happening in the classroom right now that might give you some clues? If the vinegar is still there or not?

...

Ms. S.: So what kind of, so based on all of this stuff together, what would be your prediction? Could you offer a.... You can use the board, or you can just explain it. It's up to you. What do you think might be happening?

Carl: What might be happening? Well, it's kind of silly, but oh well. [drawing on board]. This is greatly enlargenated.

...

Carl: I don't know if this accurate or not. This is H and two Os. It's actually $HO_2$.

...

Ms. S.: That's what's left of the baking soda?

Carl: That's what I think, anyways. It's my theory.

Ms. S.: So we still have $NaHCO_2$, $CO_3$, and the NaH came from the vinegar?

Carl: Yeah. It could be even CCH or HHH or OOC or CCO. It could be anything.

Ms. S.: Well how come -

Carl: It could be any combination out of this. I just picked these three because they were easy and fast.

...

Ms. S.: Okay. Questions for yourself?

Carl: I haven't thought of questions for that yet. I'm not to that.... I'm not into that far of a stage yet.

Ms. S.: Could you do that now?

Carl: Uh, how come it would pick the particular path through here [showing on diagram]. Maybe it's magnetic. I don't know. Maybe this makes some kind of magnetic force [showing on diagram] for the three molecules that come from here. So it just cuts right through there.

...

Carl: It cuts it off. And what is the formula for the new substance? Again, I do not know.

...

Carl: With the right equipment....

Ms. S.: Which would be?

Carl: Um, most likely lots and lots of testing materials to tell what is in stuff. Like, I would have to know what we're...what reacts with whatever else. So if I take a drop of, let's say, something that reacts with hydrogen, and I drop it in there, then I'll know there's hydrogen in there. If I have something that reacts with carbon, then I know there's carbon in there. Then oxygen, there's oxygen in there.

Ms. S.: So you're looking for indicators?

Carl: Yes.

Ms. S.: Okay. Chemical indicators are one way, yeah.

...

Carl: Except for what is the formula for the new substance. Still, the question is getting annoying. I'm sure you could think of something.

...

Ms. S.: Okay. More questions for yourself? What can you do to further develop this theory?

Carl: Uh...I don't know. I do not know. Haven't a clue. Not the slightest.

...

Carl: I don't completely know how it does that. I don't know how it neutralizes it. I could find out.

Ms. S.: How?

Carl: By means of communication? Book, e-mail.
(Chemistry Interview, May 25)

Carl was clearly becoming frustrated and annoyed with my persistent questioning. At this point, I decided to help him out a little by suggesting he look for patterns in the lists of acids and bases that I had given them during class. He regained interest in the interview at this point, and once again became actively involved in building his theory:

Ms. S.: Now you seem to have.... You talk a fair bit about acids and bases. What happens when they mix?

Carl: They react.

Ms. S.: Right. And then what? How do they react? What happens after they react?

Carl: Then they're neutral for a while, and then, so far in our tests in the classroom, they turn basic.

Ms. S.: Okay. And you had a theory for that. So what if you looked at some other acids and bases?

Carl: What I'd like to try sometime, was that table of the.... There's bleach and human blood and....

...

Ms. S.: pH? Oh, it's somewhere in the Grade Nine section - somewhere near the beginning. No, not near the beginning. If you go to the Grade Nine "Table of Contents," and there's a section that says "Acids and Bases."

Carl: Will it be in the titles or the sub-titles?

Ms. S.: "Acids and Bases" is a sub-title of "Chemistry."

Carl: There we go! I would like to try [looking in his book].... This is bugging me. Oh, hey. It's page forty-three.

Ms. S.: Well, the "Acids and Bases" section starts on page forty.

Carl: All right. I would like to try, not in the classroom or anything, but battery acid, which is .5 on the acidic, and drain cleaner which is 13.8.

Ms. S.: Yeah, you'll have to be awfully careful with both of those, 'cause they'll burn you.

Carl: And baking soda is 8.2. Close. 1.2 off of neutral, and vinegar is 2.2. Human blood and milk are the closest.

Ms. S.: And what would you like to do with all of those?

Carl: I'd like to try drain cleaner and battery acid.

Ms. S.: In order to find out what?

Carl: Um, if the greater of the acid and basic - acid and base - if the number of that depends, er, determines how big the reaction is. So, if I do normal rain and Great Lakes water or milk and human blood, it doesn't react too much, right? Then I do baking soda and normal rain, it should do a little bit more of a reaction.

Ms. S.: How would you measure the reaction?

Carl: I don't know. Under the microscope, I guess. How long it lasts. How fast it goes. And then I'd try normal Great Lakes water and tomatoes, and then I'll try apple and milk of magnesium, then ammonia and vinegar and ammonia and lemon juice. Then I want to try drain cleaner and battery acid. And each one of those that I went through should have a little bit higher of a reaction than the other one. Lemon juice and vinegar are pretty close. Lemon juice is a 2 and vinegar is 2.2.

...

Ms. S.: Do you think that that OH might have something to do with the way bases react?

Carl: Maybe.

Ms. S.: What do the acids have?

Carl: They only have H.

Ms. S.: Do you think that might have something to do with the way acids react?

Carl: The H reacts with OH. I don't know.

Ms. S.: If it did, what would you get?

Carl: Water. Cool. Neato.

Ms. S.: Why?

Carl: Why is it neato? Well because they neutralize each other, and water is neutral.

Ms. S.: So do you think that provides evidence for that theory?

Carl: Yes. Wait a minute [working on board]. So if these two mix, they can make AOOHOH and OH.

...

Carl: Well, this is acid, so maybe oxygen is kind of fuelling the fire, 'cause oxygens are fuelling the fire. What comes out of fire?

Ms. S.: Carbon dioxide.

Carl: Oh, cool. That supports that theory also, 'cause I know that that's what comes out of it, too. 'Cause that's what comes out of this mixture. So, if some of the extra O's are fuelling the fire, then out comes $CO_2$ gas.

Ms. S.: If it's the same type of burning.

Carl: Yes, if it is the same type of burning. I doubt it, because there is no heat involved.

Despite this brief rekindling of interest, Carl's summary comments reveal at least part of the source of his frustration with further development of his theory:

Ms. S.: So how comfortable are you with your theory that you currently have about how things become neutral?

Carl: It's hard to say.

Ms. S.: What do you mean?

Carl: Because there's zillions of ways that you could, that one person could think of, that explain why or how these two things mix or what they do when they mix. And this is just one in a sea of zillions, so it could be right, it could be wrong, it could be a little bit of both.

Carl's comments demonstrate a strong belief in objective reality, but his frustration indicates his belief that it is difficult or impossible for him to develop a correct theory: Is it ever possible to find out which, if any, of the zillions of theories is correct? He seemed to have faith that scientists are somehow able to sift through these zillions, as evidenced by his desire to find answers on the Internet or by e-mail. This apparent belief in absolute authority may also have driven his frustration in that it suggests scientists have already figured out an explanation that currently works and that has greater explanatory power than any that he could come up with in science class. However, both his prior enthusiasm for figuring ideas out on his own and the quick rekindling of interest that he displayed when shown new ways of interpreting the situation suggest that his difficulties are rooted in something deeper than an aversion to figure out that which has already been explained.

The following dialogue documents one instance in which Carl did consider the fallibility of relatively established knowledge:

Carl: Has anybody ever seen an atom?

Class: No.

Carl: Then how do we know that it even exists?

Ms. S.: Good question. Any ideas?

Class: [everybody talking at once]

Carl: No, have they ever seen one singular atom all by itself?

Keith: You could never.

Carl: Then how do you know it exists? How do people know it exists? It could be just a myth that caught on and kept going. (Class Discussion, May 25)

Further development of understanding regarding how we know that atoms exist could be just what Carl needs to strengthen the connections (and distinctions) between his own means of theory-development and those used by scientists.

It is significant that Carl's epistemological battle likely would not have occurred had the required questions been limited to the practical ones advocated by Duckworth (1996) or the "orthodox" ones implicated in Wong's (1996, p. 503) discussion of students' reactions to questions of this type. "How" and "why" questions are not easy to answer, but they lie at the heart of science. Students need to learn strategies to deal with them. These strategies include an appreciation of the nature of science that allows them to cope with the types of frustration that Carl demonstrated in the situation just described.

#### 4.3.3.3. Level 3: Deliberate search for implications.

As students work through the discrepancies that often become apparent when they attempt to construct cohesive explanations of phenomena that take into account a broad range of observations, at least some of them come to the realization that it is almost always possible but not always plausible to explain away discrepancy via alterations to their theories. This realization is partially responsible for the epistemological relativism that is so evident in many of Carl's comments, and is closely related to the discomfort that Robert adamantly displayed toward Level 2 FOI's WWHI questions. Moving from the dissatisfaction evident in both of these situations to an understanding of the need to identify testable implications is by no means an obvious step, and none of the students in this study made this transition. Robert, whose dissatisfaction with both ad hoc theories and with what he perceived as irrelevant WWHI activity, came very close to articulating this recognition.

In the discussion of the evolving classroom context, a dialogue was presented that demonstrated Robert's clear discomfort with a what-if question asked by Frank. He struggled to articulate just what it was that he found troublesome in this formulation, but was unable to do so. I, too, struggled to distinguish between what struck me as useful and futile what-ifs. My own resolution of this difficulty was important in distinguishing between internal and external variables and between Level 2 and Level 3 FOI. At the time of Robert's struggle, however, I was unable to offer such clearly articulated feedback. Frank's question seemed like a good one, but I recognized Robert's doubts as similar to ones that I had experienced in similar situations. Reflection on my response and on the diverse what-ifs posed by class members throughout the study period led me to the recognition that the identification of predictive implications, which are essential to evaluating scientific ideas, are also based on the WWHI formulation. The students came close to distinguishing between productive and non-productive what-ifs in the following excerpts from one of their class discussions during the chemistry unit:

Frank: Okay, you said there was a plus and plus atom. What would happen if an atom got in there that was negative [into the vinegar and baking soda mixture]? What if it was negative?

Jennifer: Then it probably.... Like, if you had a plus, plus, negative, or if you had a plus and a negative?

Frank: Then it would attract it.

Jennifer: Yeah.

Frank: And that's what makes the gas, or what?

Jennifer: Okay.

Ms. S.: While she's walking up, what kind of question did Frank just ask? Can you repeat your question, Frank?

Frank: What if?

Ms. S.: Is that the same sort of question as how or why, or is that a new kind of question? Like, what if this happens?

Class: I guess it's a new one.

Robert: It can't be just possibly, or maybe, it kind of has to be exact or else it kind of sounds funny.

Ms. S.: Is it helpful to say, "What if...?" sometimes?

Robert: Yes, but it just sounds wrong.

Ms. S.: Why? What do you mean?

Robert: Well, it sounds like maybe this is a question or maybe this isn't. That's what it sounds like.

Ms. S.: Comments? What do you guys think?

Samantha: What do you mean? Maybe this is a question and maybe it isn't. Like, Frank just asked her a question. Either you answer it or you don't.

Robert: But what if there is a plus atom or what if there isn't? Okay, so he said, "What if there is a minus atom with the baking soda?" Well, what if there isn't? We don't know.

Frank: It's a question. It's just like a question. What if she's wrong about it? So, I'm just saying what if. What would happen then? I'm asking what would happen then if there was a minus atom.

Matthew: Maybe she's right. We don't know.

Frank: Yeah, maybe.

Robert: So, it's kind of like a question that's just dangling there. She can either answer it, or she can say it's never going to happen. You've got to be specific.

Ms. S.: Well, if her theory is true, could that ever happen? Like, if a plus attracts and a minus.... If plus attracts plus and minus attracts minus, but if they're different, they repel. Is that what you said? Say your thing again.

Jennifer: I have a vinegar atom and I have a baking soda atom. They are both positive and they repel. I think Frank said -

Matthew: What if you had a plus and a negative atom in there.

Frank: Let's say the baking soda was a minus, and then you'd have vinegar is a plus.

Samantha: It's almost like a question of what will happen then? Like, Jennifer, you don't know if it is plus and plus. If they're both plus and plus, but Frank's thinking up a new idea. Well, let's say the baking soda is minus and the vinegar is plus, then what will happen? Jennifer's whole idea is "What if...?" because she doesn't know.

Frank: But other people don't know.

Jennifer: Remember when I did this test, and it had all the old baking soda with the new vinegar? So, this is it after it dried up. Well, everybody saw it when it was all new, right? And there was this little layer of baking soda on top, right? That was the new baking soda after.... This is hard to explain. I had the old baking soda, then I put new vinegar in at the beginning of one period. Then I let that dry a little bit.

Then in the middle, I put a different layer - like a new layer of baking soda on, and everybody saw that it didn't go in with the others.

Ms. S.: So, you mean it didn't fizz when you added more?

Jennifer: No, it didn't fizz. So, I'm thinking that maybe the new stuff was a positive, and the other two were negatives, so the negatives didn't fizz, because it attracted the positive.

Ms. S.: Which attracted then?

Jennifer: The two negatives and the one positive. They attracted, 'cause it didn't fizz.

Ms. S.: So, when they attract, they don't fizz?

Jennifer: Yeah.

Ms. S.: So, when the vinegar attracts the baking soda, they don't fizz?

Jennifer: Yeah. That's what happens.

A little later during the same discussion, Robert struggled to identify the relevance of one of his own what-ifs. Frank cut the metacognitive discussion short by identifying implications for Robert's what-if, and the discussion took a very productive turn. Unfortunately, although the articulation of implications essentially led the discussion down a productive path, the students did not identify this directly, and I did not encourage adequate reflection on the matter:

Robert: How would a positive get into a negative? Jennifer, a positive and a negative attract, so wouldn't the positives in the vinegar attract to the positives from somewhere else [going to the blackboard]? Here's your happy positive guy, and here's your little minus guy. This is somewhere else. Somewhere out in the air. This is in your vinegar. Now these attract, so when this got into here, it attracts it to your plus guy. And then you've got a minus to a plus.

Samantha: I have something for Robert. This is going back to that what-if-question thing. Don't make a face. You just asked one of those, Robert.

Robert: Okay, if....

Samantha: For sure, the minus would go into the plus, because they attract to each other.

Ms. S.: But, Robert, didn't you start that with, "What if there was a negative in the air?". Was it helpful for you?

Robert: Yes.

Ms. S.: So, what don't you like about it?

Robert: I don't know. It's like it could happen or it couldn't.

At this point, Robert explicitly recognized the SWIID formulation critical to Level 3 FOI. However, he still had not identified the role that identifying testable implications may play in making what-if questions relevant.

In the next segment, Frank identified an implication of the WWHI question that was being challenged, and the discussion became centered on these implications. However, the consideration of the implications occurred at the level of the theory itself, and a more general discussion of the role of implications did not take place. Had I been more alert to this, I could have encouraged the students to identify what in Frank's comment suddenly made the what-if question productive. As it happened, the students became caught up in the argument and forgot that the nature of the question itself was the original focus of the discussion:

Ms. S.: So, what about that?

Samantha: What-if can go on forever.

Frank: What if these pluses are in the vinegar, right, and there's a whole bunch of plus and negatives over there, so they will attract in the vinegar. That's just like this right here, except it's inside the vinegar.

Robert: Yeah, but then according to Jennifer's theory....

Frank: She'd probably say that there's more plus than negatives. There's atoms all around us, aren't there?

Robert: Yes.

Frank: So they'd come out of the boards.

...

Frank: Okay, on this picture here, I got this out of that chemistry book, and right here, there is a whole bunch of plus and negative atoms stuck together. So, let's say there's a negative and a plus inside the vinegar. They'd attract, plus the plus and negatives out of the air would just come flying in, wouldn't they? 'Cause the air is filled with them.

Matthew: But it's filled with them.

Robert: The vinegar has plus and minus in it, the baking soda has plus and minus in it, and you mix them together, and there's really nothing happening.

Frank: And so Jennifer's theory.... There'd only be plus and plus and a few minuses, and she thinks that they will repel, and that will cause the gas. But how will it cause the gas, and then this theory says there's atoms all around us. Well, all of them would come in and attract.

Robert: Now this minus and this minus aren't pushing back. The plus is holding them together. They're touching, but they're not repelling, so-

Ms. S.: So, what are you saying about plus and minus then?

Frank: Well, there'd be lots of plus, right, and then a few minus. So the plus would be stronger, and they'd repel and cause the gas. Well, wouldn't all the other atoms come rushing in, and then they'd have a big goop of them in this beaker.

Ms. S.: So it wouldn't just react with each other, it should react with everything else?

Frank: Yeah, and then they'd all come in and just stick together, 'cause there's atoms all around us in the air. And how would it create gas anyway?

Robert: That's still what I want to know. (Class Discussion, April 27)

Samantha was right in asserting that "what-if can go on forever." However, Frank's and Robert's subsequent identification of implications for the WWHI question that Frank originally posed made it testable and provided focus for the continuation of the development of the theory. As Sagan (1996) pointed out in his "baloney detection kit," "Propositions that are untestable, unfalsifiable are not worth much" (p. 11). Although the students did not articulate this distinction, their discomfort with certain forms of WWHI questions and their solutions to the difficulties that they posed could have provided a rich context for further reflection on this topic. If the students had made explicit the value of WWHI predictions, they may have been able to take advantage of their ability to identify or perhaps even to seek implications that would have made their propositions testable. Future research is needed to determine whether this is something that indeed occurs.

#### 4.3.3.4. Level 4: Alternate implications.

As students learn to take advantage of their ability to identify testable implications, it seems likely that they could encounter situations in which different students identify alternate and possibly conflicting implications for the same theory. This could lead to the realization that even the confirmation of predicted implications does not offer definitive proof of their ideas and may be a critical understanding in the development of an understanding of the theory-dependence of knowledge. It seems quite conceivable that students more effectively guided toward a Level 3 IE understanding could, through further reflection at this higher level, progress to the hypothesized Level 4 discussed here.

### 4.3.4. Empirical procedures.

In developing the categories to describe the methods by which children construct scientific understanding, the primary focus was placed upon the mental processes involved in generating and evaluating ideas. In this section, I focus on more traditional process skills such as fair test procedures, measurement skills, and methods of data analysis, but do so in a manner that also emphasizes generalized thought processes over skill in specific techniques or tools. There is considerable overlap between these categories and the FOI and IE frameworks, but I have included them to demonstrate their continued relevance in the context I have developed. As with the other categories developed to this point, the progressions are based on understandings that seem to occur naturally in familiar contexts, and emphasis is placed on the role of reflection in developing abstracted understandings that may be more systematically applied.

At this point, it remains unclear whether the understandings discussed in this section are used more consistently once students have been able to articulate them in a generalized form. This is something that will need to be monitored over a longer period of time. For example, although there is some evidence that students were able to apply fair-test procedures in a generalized fashion, this was not always a rational process. The formulaic approach that was evident in some students' work does not suggest a true abstracted understanding of a controlled experiment. It does, however, lend credence to the idea that generalized understandings may be more broadly applicable. If they are developed in a rational fashion, it seems likely that they would also be applied more rationally.

### 4.3.4.1. Controlled experimentation: What is a fair test?

Understanding the need for fair test procedures is something that appears to be quite easy for students at this age, but this understanding may be more superficial than it appears at first glance. All of the students were able to perform controlled tests, whether in the context of a controlled experiment aimed at testing a theory (Level 3 FOI) or in the context of a controlled test designed to determine the effect of a particular stimulus in a given situation (Level 2 FOI). As will be shown, however, this may not always reflect a rational understanding of the need for a comparison sample, and in some cases was at least partially the application of a homily stating that "Everything except the thing you are testing needs to stay the same." In situations where students questioned the results of a particular suggestion or demonstration, they were able to suggest alternate variables that may have led to the observed results, but a generalized understanding of the importance of this procedure was seldom articulated. This does not prove a lack of understanding but certainly provides no clear evidence that it does exist. Domain-specific appreciation of the possibility that other variables may have affected a particular test is included with Level 2. The examples provided to support this level may profile students who in fact have a higher or more abstracted level of understanding, but this understanding was not evident in the dialogues. At Level 3, clear understanding of the importance of fair-test procedures in allowing comparisons of experimental samples is articulated. Even at this point, however, the importance of considering what hidden variables may have affected a test is often clear only in hindsight. The systematic ability to think beyond variables that are readily apparent is reserved for Level 4. This is a hypothetical category in that evidence of students at this level was not observed. Level 1 is also a hypothetical category in that all of the students were able to recognize the possible effects of other variables on the tests that they conducted. It is included as an extrapolation of Level 2, but evidence from studies of young children would be necessary to validate its existence.

#### 4.3.4.1.1. Level 1: Assumed causation.

It seems likely that students with little exposure to different views regarding causality would have little understanding that a variety of different factors could be responsible for an observed event. As a result, they may simply assume that the first factor that they identify is responsible for observed phenomena. All of the students in this study were able to consider alternate possibilities, although they did not systematically seek them.

#### 4.3.4.1.2. Level 2: Domain-specific fair-test procedures: How do you know it isn't the...?

As students debate their ideas, alternate views make apparent the possibility that causation may be viewed in multiple ways. In the examples presented here, the students identified possible alternative explanations to the ones being suggested. Although their questions demonstrate their ability to question important assumptions when their understanding of specific content made apparent the need to do so, it is unlikely that this was a more generalized skill.

Just prior to the discussion in the following excerpt, I had shown the students a wet cell that used Drano as the electrolyte and had suggested to them that they touch the beaker to feel how hot it had become:

Class: Wow. That's warm.

Ms. S.: Don't stick your finger in there.

Rachel: Was that warm water that we used?

Ms. S.: Yeah. Good question, Rachel. That was cold water, right Carl [Carl had filled the beaker]? If you touch this one, that was how warm the water got. That was a good question, Rachel. Without knowing that, it's hard to tell isn't it? (Class Discussion, March 30)

The next example took place as Jordan was explaining the effect of vinegar on an ohmmeter:

Jordan: This charger or whatever it's called - a tester - is going to make its own energy, and when you put two [probes of the ohmmeter] in the same one, it creates energy, but when you put it in one or the other, it doesn't.

Ms. S.: So, is it creating energy or is the tester creating energy?

Jordan: The tester. It's contracting.

Ms. S.: But, it's kind of like a bulb. If it.... If you connect it, the bulb will light, right? And if you don't connect it, what happens?

Class: The bulb won't light.

Ms. S.: So, if you put them both in the same tray, is that connected or not?

Jordan: Connected.

Ms. S.: So, what does that tell you about the liquids in that tray?

Keith: The electricity passes through the acid in there.

Ms. S.: Do you guys agree with what Keith just said?

Class: Mm Hmm.

Ms. S.: Did you hear what Keith just said?

Robert: Yes.

Ms. S.: All right. And how come it doesn't work when you put the testers in two different compartments?

Keith: 'Cause then it can't pass through the vinegar.

Ms. S.: Now, Jordan, you made a comment about that - regarding comparing it to batteries.

Jennifer: I have a question. When you put those two ones [the probes of the tester] together, does it show up on a tester sort of thingy?

Jordan: Uh.... Yep.

Ms. S.: Okay. Good question, Jennifer!

Jordan: Very high.

Jennifer: So when you put them both in the same one, how do you know they're not touching?

Jordan: They aren't.

Jennifer: They could be.

Keith: Just with the acid.

Ms. S.: Go take a closer look, Jennifer, if you don't believe him.

Keith: The electricity is passing through the acid.

Jordan: Then what I think the acid does is that it flows through the water to this one, so that it makes a connection. You can't get that when you put it in different ones, because they can't get to each other [demonstrating to class].

Jennifer: 'Cause it only passes through the acid.

Robert: What if you had a thin connection, just a little bit of vinegar on the top? Going over.... Or a piece of string?

Jordan: Uh....

Robert: Get a piece of string with vinegar on it.

Jordan: Yeah. Where's that piece of string?

Ms. S.: Maybe, check with Ms. M., 'cause I don't think we have any on our cart.

Keith: Can't we just use wire? (Class Discussion, April 20)

In both of these cases, the students displayed reservations about the points being made by the demonstrators. As a result, they suggested alternative explanations. Although this was useful, it does not represent an articulated understanding of why it is important to consider alternatives in all cases, nor does it demonstrate an articulated understanding of the criteria necessary to ensure a fair test.

#### 4.3.4.1.3. Level 3: Abstracted fair test procedures.

A Level 3 understanding of controlled experimentation was somewhat difficult to analyze. All of the students demonstrated clear understanding of the idea that for a test to be fair, only one variable should be changed at a time. However, not all of them applied this understanding in a rational manner. There were some instances that suggest that apparent understanding may have been little more than the memorization of a rule for which the rationale for application was unclear. This issue was particularly evident in instances where two or more variables could not be controlled simultaneously. Cases such as these necessitate a rational choice regarding which variable is most likely to affect the test. In other cases, students tended to assume that a single variable was the only factor affecting the test. A single stimulus can generate multiple effects. The ability to consider these factors systematically is dependent upon a true understanding of the need to control variables and is not effected by the rote application of the homily that states, "You must only change one variable at a time to have a fair test."

As Rachel and Keith conducted tests involving different numbers of batteries and bulbs within various circuit arrangements, Rachel expressed concern that the batteries were weakening as the tests progressed. She wanted to use fresh batteries, but Keith insisted that to change to new batteries would not be fair. However, switching to new batteries would have better maintained a constant voltage, which was really the factor that needed to be controlled.

In a similar instance, Rachel and Samantha experienced pragmatic difficulties trying to connect five alligator clips to the same terminal of a C-cell. Rachel suggested that it wouldn't really matter if the clips were fastened to one another and only one of them touched the terminal of the battery, but Samantha was adamant that all of the clips needed to touch the battery. Rachel rationalized her choice by suggesting that each bulb still had direct access to the terminal of the battery (Field Notes, February 13). It is unclear whether Samantha's reluctance to accept this rationale was due to her being unconvinced that the two situations were actually the same or whether she was merely blindly adhering to a rule she thought was important.

There were cases, however, where students very clearly articulated rationales for controlling variables in a manner that seems to indicate a more generalized understanding of the importance of doing so. In the following example, Samantha very clearly justified the addition of a control sample for the purpose of comparison:

> Samantha: I just thought of a test. We were talking about distilled water and stuff, right? Okay, you know how Jennifer's doing that vinegar-evaporating thing where you take the vinegar and you put it in a petri dish, and so far we've

said that it's pretty much the water that goes up to the top - that evaporates - and then we test with pH and the water-paper [cobalt II chloride test paper] thing. Well, if we do that with distilled water, since it's probably distilled water that's in the vinegar, if we do that with distilled water, then shouldn't it be sort of the same? Like, shouldn't it be a close pH?

Robert: What's the point of adding more distilled water? And it's already got distilled water.

Samantha: We're not adding anything. We're doing a whole different test.

Ms. S.: Like to compare the two.

Samantha: Yeah. Like to see if the vinegar is.... 'Cause we're saying that it's the water in the vinegar that's evaporating to the top with maybe a little bit of vinegar. We're going to do the exact same test, but just with distilled water. If it evaporates to the top, when we pH that and when we pH the vinegar water, then the water on the top of the vinegar lid.... Shouldn't they be pretty close to the same pH?

Ms. S.: So it would give you something to compare it to? We call that a control in science. Good point.

Robert: So, what do you mean with plain distilled water and then this vinegar water?

Samantha: Okay. You have your petri dish or whatever full with the same amount of vinegar and another container that is the same, and then if the vinegar....

Robert: I know all that. What's in the other petri dish?

Samantha: Distilled water.

Robert: Just distilled water?

Samantha: Just distilled water.

Robert: Then what's the point of that?

Matthew: We're going to see if there's distilled water in the vinegar.

Samantha: Yeah. We're saying that there's water in vinegar. Well, we're saying that when it's over there evaporating that it's the water that's evaporating to the top.

Robert: Well, we just found out today from the pH that the stuff that does evaporate does have acid in it [droplets on the lid of the petri dish were acidic].

Samantha: But we didn't know if that was a fair test or not. So, what we're going to do is, if it's the water that evaporates to the top, even with a little bit of vinegar in it, and then the distilled water when it evaporates to the top, if we flip the lids over and pH them, shouldn't they be pretty much the same? If it's distilled water on the top, then the vinegar would be distilled water too?

Robert: No. Vinegar has acid in it.

Samantha: But they're not going to be the exact same. I said pretty much the same.

Ms. S.: Isn't what you want to find out is if it has acid in it or not? Like when it evaporates, does it have acid in it? That's the question.

Samantha: Yeah, and if the distilled water is just going to be distilled water, but if the vinegar goes to the top, and it's close to the same pH, then we know that it's distilled water that's evaporating.

Ms. S.: Not vinegar?

Samantha: Right. But if it's like really far off, like if it's more acid than the other one, but if it shows to be pretty much the same, then that would mean that it's water with a little bit of vinegar in it. (Class Discussion, May 22)

During her chemistry interview, Samantha demonstrated an ability to reflect upon the importance of including water and salt as a control sample to determine whether in fact vinegar and salt chemically react. Although she required considerable guidance to reach this conclusion, at the end of the interview, she clearly articulated a generalized statement regarding the importance of a control sample:

| | |
|---|---|
| Samantha: | Well.... His [Robert's] idea was that baking soda - that sodium is the active ingredient. We'll have to tell him, "Why doesn't vinegar and salt react?" |
| Ms. S.: | And he will probably tell you that it does under the microscope, because he put it under there, and he saw bits of the salt breaking off into the vinegar. |
| Samantha: | But why doesn't it fizz like real - like baking soda and vinegar? You can, like, see it fizz. |
| Ms. S.: | Now you had mentioned making something to compare it to for your experiment. What might Robert compare his to? Like, he did vinegar and salt, and he thinks that that might be a reaction, because it's disappearing. But you don't think it's a reaction. You.... Because it doesn't fizz, you said. |
| Samantha: | Well, maybe it's because vinegar and baking soda, they give off a gas, so then the gas can come up, and that's what the fizz is, like I said before. But I don't think salt and vinegar make a gas. |
| Ms. S.: | So, you're saying that it might be chemically reacting, but not making a gas [Is she?]. I hadn't thought of that. That's an interesting point. One thing I had suggested.... That's actually really good that you had thought of that. Another thing that I had suggested to Robert is that he put salt in water under the microscope and watch what happens. Do they chemically react? And what happens when you mix salt and water? |
| Samantha: | They probably don't do anything. |
| Ms. S.: | So the salt stays there in lumps of crystals? What happens when you put salt in water? |
| Samantha: | It dissolves. |
| Ms. S.: | What do you think that might look like under the microscope? |

Samantha: Tiny, tiny, tiny.

Ms. S.: Okay, but you wouldn't see the salt dissolved under the microscope, but what if you had salt crystals and water and you put it there. Could you see anything? What do you think the crystals would be doing?

Samantha: Wouldn't it be bits coming off of the whole salt particle?

Ms. S.: And once they break into small pieces, can you still see them?

Samantha: Maybe. Well, if they break into small pieces, then they're dissolved so, no.

Ms. S.: You could if you had a way more powerful microscope, but not with our microscopes. So what I had suggested to Robert is that he compare what salt looks like with water compared to what vinegar looks like with salt. Why do you think I suggested that?

Samantha: Like, we're doing the same things.

Ms. S.: So my theory was that the salt and the vinegar wasn't reacting, but was.... Why would I want to compare it with water? What is the salt doing in the water?

Samantha: It's dissolving, and like little parts are breaking off, and then in vinegar, that's what he said it's doing, too.

Ms. S.: Well, he said it's chemically reacting and making new things. Is dissolving making new things?

Samantha: Uh huh.

Ms. S.: So saltwater has something new that salt and water don't have?

Samantha: But salt and water, neither one's an acid, though. And vinegar is an acid. So, it's, like, stronger. Salt and saltwater, they don't really.... Well, it's dissolved, but when it's dissolved, it's still there, though.

Ms. S.: It's still salt and it's still water?

Samantha: Uh huh. And when you mix baking soda and vinegar, the particles of the baking soda breaks off and lets go into the vinegar, so it's joining with something different. In saltwater, there's nothing different.

Ms. S.: So what about vinegar and salt? Do those have to be chemically reacting, or can they be dissolving just like the salt and water?

Samantha: They can just be dissolving, too.

Ms. S.: So why would I want to see what salt and water look like under the microscope?

Samantha: Well, if the vinegar and the salt are dissolving and the water and the salt are dissolving, then you can compare the two. Because you know that water and salt.... You know that they dissolve, but that might be the way to test if salt dissolves in vinegar, or if it's a reaction.

Ms. S.: 'Cause Robert's using that to support his sodium theory. But, like what you said before is that it didn't even fizz. So, the sodium isn't necessarily reacting. So by doing that, would you get some support for your -

Samantha: Yeah, because.... Well for him, like, he's saying that the sodium is making the chemical reaction or the salt particles break off. Well, if it does the same thing with water, then you can say that it's just dissolving and not a chemical reaction. I know this, because this is the same as that. Well, this is dissolving and not chemically reacting.

Ms. S.: Do you think that would be important for Robert to do before he says that it's chemically reacting?

Samantha: Yeah, 'cause they're the exact same. He can't really say that the water and the salt were chemically reacting.

Ms. S.: Kind of another control. Because of what you were doing up there with the distilled water, right? You had to have something to compare it to. Here again, you have to have something to compare it to. We call that a control. Scientists use them all the time.

Samantha: Well, if you have nothing to compare it to, then you're always right. 'Cause if Robert just took that and didn't compare it to water and salt, then he can say, "I'm right, 'cause this happened." He can just say that, and then I can say, "Well look at this salt and this water, it's doing the exact same thing. Prove I'm wrong." Basically, we're just saying, "I'm right," because it does this. (Chemistry Interview, May 28)

In this discussion, Samantha made an important step toward transcending Level 3 FOI verification strategies. If she continues to reflect on situations such as the one presented here, it seems plausible that she could progress toward strategies that exemplify systematic disconfirmation. A Level 4 understanding of the need to anticipate factors to control could thereby also contribute to the achievement of Level 4 FOI.

#### 4.3.4.1.4. Level 4: Understanding the need for a control.

A generalized understanding of the need for a control sample is something at least some of the students in this study were able to achieve. However, it is one thing to recognize with hindsight the importance of a comparison sample, and quite another to think ahead to question, "What else could have caused those results?" so that necessary controls may be put into place.

Even renowned scientists did not consistently use a control until it became an established part of the scientific method. For example, Spallanzini's experiments to determine whether microbes could be spontaneously generated did not involve a control. He prepared nineteen sealed flasks with liquids prepared by boiling a variety of substances such as barley, eggs, and corn, immersed them for one hour in boiling water, and, finding no microbes present in the resulting containers, proclaimed that spontaneous generation could not occur (Melnychuk, Jacknicke, & Visscher, 1970). Had he been aware of the need for a control, he should have prepared matching samples that were then left in contact with the air. Today, the scientific method is an accepted way of doing science. However, when students learn the method without first understanding why it is necessary, they do not gain a true understanding of its importance.

#### 4.3.4.2. Measurement devices and techniques.

Learning to use developed measurement techniques is relatively easy. What is much more difficult is identifying the need for those techniques. This need is rooted in the development of a theory that makes valuable a particular type of data that may be obtained by using a certain device or technique. As was shown in Section 4.3.3.2, the identification of observable implications for theory is often very difficult. Sometimes, observations made with our unaided senses provide clear evidence for or against a particular theory and do not necessitate the use of more sophisticated techniques. In these cases, their use should not be considered an inferior strategy, but one that is more practical in the context of that application. Often, however, observations of this nature are inadequate. Scientists have developed, and continue to develop, observational aids and techniques that allow them to observe more adequately the phenomena implicated by their theories. Students should learn these as their investigations make them necessary, but should also learn to invent methods of measurement that specifically suit their purposes.

Developing an understanding of our own sensory fallibility emphasizes the need for accurate means of measurement. Understanding and dealing with the ambiguity of measurements based on the unaided senses forms the basis of the levels identified in this section. At Level 1, students are unaware of sensory limitations and rely fully on what their senses tell them. By Level 2, the need for consistent standards indifferent to personal bias becomes evident, and devices that provide more objective measurements of phenomena are sought. The transition to Level 3 involves an appreciation that all measurement devices are subject to some degree of instrument and observer error and that this must be considered in their selection and use. Students at this level are able to select and design instruments and methods to emphasize differences between the phenomena they are attempting to measure. Finally, at Level 4, students become aware that even careful measurements may be influenced by the expectations of the experimenter and that judgements of possible observer or instrument error are often grounded in such expectations.

#### 4.3.4.2.1. Level 1: Sensory impression.

There were many examples in which students observed during this study relied on sensory impressions as a basis for measurement. In most cases, these observations served their purposes well. In applications where differences were obvious, this was sufficient to provide evidence for or against a given idea. The change in the smell and taste of the vinegar and baking soda mixture are good examples of this in that they provided clear evidence that something new was being made. The degree of reaction of vinegar and baking soda was sometimes measured simply by noting whether the mixture fizzed "a little" or "a lot." This provided clear support for the idea that used vinegar does not create as much fizz as non-used vinegar. On the other hand, despite measuring bulb brightness with a light meter, there was one student who was convinced that the brightness measurements of the bulbs that he observed changed in accordance with his expectation that bulbs in series dim with distance from the positive terminal. For the most part, the students in this study were able to determine when more exact and consistent measurement techniques were required and relied on their senses only when adequate information could be gathered in that manner. Therefore, their measurement skills must be classified at least at Level 2.

#### 4.3.4.2.2. Level 2: Consistent standards.

Students at Level 2 employed a variety of different techniques to make the results of their tests measurable. For example, balloons were used to collect and measure gas, amount of fizz was measured by what level the bubbles reached in a beaker containing vinegar and baking soda, and pH paper was used to measure the acidity of different substances.

Many of the tests that utilized careful measurement were Level 2 FOI tests aimed at determining the nature of the effects that different substances had on one another. For example, Rachel tested the effect of mixing the following substances:

1) 25 mL vinegar + 4 scoops baking soda + 4 scoops salt
2) 25 mL vinegar + 4 scoops baking soda + 15 mL water
3) 25 mL vinegar + 4 scoops baking soda

She carefully measured all of the ingredients and made her final observations simply by observing the containers. The mixture containing salt lasted longer, but had smaller bubbles, whereas the one with water had more bubbles and didn't last as long (Field Notes, April 2). In another Level 2 FOI test, Rebecca tested the effect of mixing equal amounts of the following substances by measuring the diameter of a balloon used to collect the resulting gas:

1) vinegar + baking soda + distilled water
2) vinegar + baking soda + tap water

Although these examples provide evidence of careful measuring skills, it is important to remember that a focused test (Level 3 FOI) that relies on data collected without the use of measurement or observation tools is a better aid to theory-generation than an unfocused test that uses precise measurement techniques.

The replication of experiments is often emphasized as an important method of validating experimental results and is consistent with a Level 2 understanding of the need for careful and consistent measurement. Students' understanding of replication may not always mirror that of scientists, however. Rebecca's use of a second set of data suggests that even this outwardly straightforward process may not be fully grasped by all students. After her first distilled vs. normal water test, she noticed a small difference in the resulting diameters of the balloons she used to measure the amount of gas generated in her test. I asked her if she thought this was due to a difference between the water-types or if it could have been a measurement error. She responded by indicating that she would retest it to be sure. When she came to me to report her results, I asked her how they compared to her original results, and she said that she couldn't remember (Field Notes, May 11). Apparently, her goal in repeating the test was to ensure that the results were valid simply by taking special care to ensure that all parts of the investigation were carried out with care. This approach could be based on a lack of understanding of probability. Unless there is a consistent flaw(s) in the measurement procedure or apparatus, two sets of results that are nearly the same are more likely to be accurate, but only because the laws of probability suggest that it is unlikely that errors would emerge in exactly the same way each time the test is done. Failure to understand probability does not demonstrate a lack of understanding of the need for consistent standards of measurement, but this incident does point out a misconception that may need to be challenged with other students as well.

#### 4.3.4.2.3. Level 3: Emphasizing differences and understanding significant error.

At Level 3, students make conscious efforts to observe and measure in ways that emphasize the differences they are trying to discern. This may be as simple as placing samples for comparison in close proximity so that their effects can be observed simultaneously, as Jennifer did to compare the effect of adding a third bulb to a parallel circuit. In this case, she arranged her circuit in a way such that by moving a single wire, she could quickly alternate between a two and three-bulb arrangement, thereby observing what were in fact very small differences between the brightness levels of the bulbs. In comparing relative brightness in this manner, she was actually able to detect differences that the light meters could not. In another instance, Rachel switched from a short, fat container to a tall, narrow one to better observe the amount of fizz generated by the different reactions she was investigating (Field Notes, May 13).

Observing significant differences is not always as obvious as it was in these cases, however. After completing their circuit tests, the class reached an informal consensus that a difference of two on their light meters could represent observer or instrument error. However, most did not make systematic use of this decision when they analyzed their data. In itself, a student's recognition of potential error is not sufficient to classify him or her at Level 3. They must then use this information to make rational decisions regarding whether the amount of error is enough to invalidate results. If so, the instrument or the method needs to be improved so that differences are more readily apparent.

The following dialogue was part of a larger discussion regarding whether heat is a particle. In it, I suggest to the students that if it were, it should have mass, and that hot substances should weigh more than cold substances. I then try, with limited success, to convey to the students how large samples of water would make differences between hot and cold samples more noticeable. In fact, this may not be entirely accurate in that devices intended for measuring larger samples are often not as sensitive as those intended for measuring smaller samples. Given the same measuring device, the larger samples could reasonably be expected to provide a more noticeable difference in the masses of the two substances (if heat has mass):

Ms. S.: We can test that. When we test that, should we use a little bit of water, like small containers, or big containers? Which way would we notice the most difference? If it had a lot of heat in it - er sorry, make those the same size. If this one is full of heat, and this one's not, or if this one is full of heat and this one's not, which one are we going to see a bigger difference in? Is there going to be a bigger difference between the big ones or the little ones?

Robert: You would see the same difference just using the bigger container.

Ms. S.: Okay, but let's say that this one weighs a hundred kilograms and this one weighs one kilogram. This weighs two hundred kilograms, okay? Then what would this be?

Class: Two kilograms.

Ms. S.: Two kilograms. So what's the difference between these two?

Rebecca: There's a hundred kilograms more.

Ms. S.: A hundred kilograms more. What's the difference between these two?

Carl: A thousand grams.

Ms. S.: In kilograms. Let's keep it fair. What's the difference between these two?

Class: One.

Ms. S.: One kilogram. So which one's going to be a more noticeable difference?

Class: The big ones.

Robert: Well if you put it into percent, it's just doubling.

Ms. S.: Okay, yeah. But which.... If we're talking about our measurement skills, you're right, they're both doubling, but which one are we going to notice doubling more easily?

Class: The big one.

Ms. S.: Won't the big one be.... Like, if you're weighing something, is it easy to be off by a kilogram?

Class: Yeah.

Ms. S.: Is it easy to be off by a hundred kilograms?

Class: No.

Robert: Yes. Because there's more kilograms to be off by. It's bigger, so maybe it would get -

> Carl: Yeah, but what about when we're measuring light bulbs. One.... A difference of one could be a mistake, but a difference of two is a smaller one [a small difference in brightness], and a difference of five would be a huge. So let's say that the one hundred to two hundred is five for measuring lights and the one to two is - could have been a mistake.
>
> Robert: Okay, but what if you're only measuring a dim bulb?
>
> Carl: Then you can still make mistakes. It's just on the bigger one, um, if it's more than a leap of one, then it'll be easier to notice, because you might think it's a mistake if we did it the other way. (Class Discussion, April 6)

This principle was not immediately obvious to some of the students and is one that they will likely need to reflect upon in several contexts before its importance is recognized in a more general sense.

#### 4.3.4.2.4. Level 4: Seeking counter-evidence.

There were several instances in which more careful measurement techniques were sought only when expected results did not conform to observed results. The students did not recognize this, but it is likely that these situations would have provided excellent reflective bases to help the students move toward the understanding that observation is often dependent on what the observer expects to see. My own explicit recognition of this phenomenon and some of the ways that it manifests itself within student investigation will allow me to take better advantage of contexts such as these.

In the following example, Frank tested the effect of mixing alcohol with baking powder in an attempt to demonstrate that because it "ain't very much of an acid" (he had measured it at pH 6), it would not react with baking soda. Robert was convinced that it should react, and suggested using a microscope to observe it more closely. Had he not been so convinced, it is unlikely that he would have made this recommendation:

> Frank: Yeah, okay. But since it's close to neutral, it doesn't mix with baking soda. It doesn't mix even if you shake it [demonstrating to class].
>
> Ms. S.: So nothing happens, eh?
>
> Robert: How about if you put it under a microscope, because you could see it a bit better, because maybe it does and you just don't know it.
>
> Frank: [holding it up to his ear] It doesn't make a sound.
>
> Robert: Well try it with a microscope.
>
> Frank: Okay.
>
> Ms. S.: Use a well slide. Do you know what those are? Those slides with the little dish in them. Now what are you testing Jordan? (Class Discussion, April 20)

The tendency to look more carefully for evidence that supports a given theory was also very evident as Robert tried to find evidence for his theory that the sodium in baking soda is responsible for its reaction with vinegar. Samantha, who did not subscribe to this theory, noted that salt does not fizz when mixed with vinegar. Robert was convinced that salt and vinegar should fizz and observed their interaction under a microscope. When he did so, he discovered that they do interact in a manner that he then assumed was a chemical reaction: He claimed that it looked like the vinegar was eating the baking soda. Robert was not wrong to look more closely into his idea, and in fact demonstrates Level 3 observational skill in his efforts to emphasize the differences that he was looking for. However, recognition of his bias in favor of the sodium theory may have helped prompt him to consider alternatives, thereby fostering transition to Level 4.

Gunstone (1994) described the use of an activity especially designed to provide a reflective context that could help his education students recognize how their expectations can bias their observations:

> Learners are shown a situation, asked to write predictions and reasons, some discussion of predictions and reasons is undertaken, observations made (and written), and any necessary reconciliation between prediction and observation undertaken (p. 141).

In the first situation that he described, a rubber ball and a shot put with equal diameters and very different masses were dropped from a height of two meters to determine which fell first. A striking correlation between the students' predictions and observations was noted. The height of drop was then extended to 9.6 meters, whereupon it became obvious that the shot fell first. This activity demonstrates both the theory-dependence of observation and the importance of designing an observational context in which results are made obvious. Ideally, reflective contexts could emerge from the students' own investigations, but events such as this could be used to reinforce understandings developed through reflection on other investigations.

#### 4.3.4.3. Data analysis.

Data analysis often relies on mathematical understandings and techniques. Inventions such as averages, rankings, and correlations are commonly used to tease patterns out of large collections of numerical data. These are powerful tools when properly understood. Students, however, often lack the qualitative understandings that make their utility apparent. Just as fair-test procedures can be applied in a non-rational, formulaic manner, the use of statistical tools before their need is made clear can be counter-productive. Essentially, all of these tools allow complex sets of numbers to be organized in a manner that allows the existence or non-existence of trends to become evident. They should not be used until students are aware of the need to find such trends.

There was limited evidence regarding the manner in which students interpreted large amounts of data. The progression identified here is largely hypothetical, but follows the general trends from assumed to evaluated and implicit to explicit that is evident in the other frameworks delineated in this study.

For many traditional methods, a certain degree of mathematical understanding is required, but this is not the emphasis here. The levels presented here are based on qualitative understandings of data. As was the case with both fair-test procedures and measurement techniques, Level 1 is a downward extrapolation from Level 2 and was not observed in the students who took part in this study. A Level 2 approach was evident in students' attempts to draw general conclusions from the data simply by relating unorganized results back to their hypotheses, often by selecting those results that confirmed their hypotheses. Students at Level 3 are able to point out examples to counter the more non-critical confirmations evident at Level 2, and may develop methods for organizing data in ways that make trends more obvious. Again by extrapolation of Level 3, Level 4 should involve the systematic consideration of alternative explanations for observed trends.

#### 4.3.4.3.1. Level 1: Conclusions based on a single case.

Although I did not observe instances in which students reached conclusions on the basis of a single observation, it seems plausible that this could occur, especially if the relevant observation confirms an expectation. When only a single case is used to establish a causation relation, it is impossible to determine whether the observation is due to that factor. When variations in one factor effect variations in another, a causal relation (be it direct or indirect) is more likely implied.

#### 4.3.4.3.2. Level 2: General impressions from the data.

After testing the effects of using different numbers of bulbs and batteries in each of the three identified circuit types, Keith was convinced that bulbs in a Rebecca-style (series) circuit dimmed with distance from the positive terminal of the battery. He explained this alleged dimming as follows:

> This style works the way is dose Because B1 [the bulb nearest the positive terminal of the battery] takes more + power witch is higher voltage than – side of the battery so it is the brightest as the power goes through #1B drained some of the pow so #2B gets even less pow so its second brightest and 3rd B is dimmest. (Journal Entry, March 9)

During his battery interview, I questioned Keith regarding whether this explanation was supported by the data that the class had collected. It is true that there was a great deal of room for error in measurement in the manner that the tests were conducted and by which the bulb brightnesses were measured, but Keith repeatedly used alleged errors to explain away any results that did not support his theory:

| | |
|---|---|
| Ms. S.: | ...So what do you think? |
| Keith: | What? |
| Ms. S.: | Well you were talking about the bulbs getting dimmer as they go. |
| Keith: | Uh, the power gets used up from here as it goes along. It's using more power. |
| Ms. S.: | Okay. |
| Keith: | For all three batteries. |

Ms. S.: And do the bulbs get dimmer as they go?

Keith: Yeah. This one, then that one, then that one. This one is the first one, because it's closest to here. Like, anything closest to here would get more power, so it's like the brightest. The second one is a little dimmer, and the third one is the dimmest.

Ms. S.: Is that what happened in the chart we just looked at [the summary chart containing each groups' test results]?

Keith: Uh, sort of. I don't know. Yeah. This one did. It started at seventeen, then it went to thirteen, to twelve, ten, nine, six, seven, two, one, one. And one and five. It got dimmer [At this point, he is incorrectly reading the chart such that the sequence of numbers he is reporting is actually the progression of numbers for one to five bulbs in a series circuit rather than the progression of bulbs within a single series circuit].

Ms. S.: And what about the others?

Keith: Yeah. Nine, six, one...

Ms. S.: Okay. But careful. This means with only one bulb. That bulb was nine. With two bulbs, they were six and eight. That's how bright the bulbs were. One was six and one was eight.

Keith: Oh, we're just looking here.

Ms. S.: Yeah.

Keith: [He is now reading from the section of the chart that displays results for one battery and three bulbs in a series circuit.] Six, eight, ten. It went the other way [decreased from negative to positive]. But then that would've been.... Who knows what order it was in.

[It is significant to note that that during a previous class period, the students had agreed that, based on their own experiences with the paper light meters, that a difference of ±1 could be due to error, ±2-4 indicated a small difference in brightness, and a difference of ±5 indicated a large difference in brightness. Of course, it would be wrong to assume that Keith fully accepted this categorization, but it is interesting that he did not even consider it during his analysis.]

| | |
|---|---|
| Ms. S.: | Okay. You mean you don't know if they started at the positive end or the negative end. |
| Keith: | Yeah. It doesn't tell you. |
| Ms. S.: | Except did we decide or no? When we wrote that, didn't we decide which end we were supposed to start at? One was supposed to be the positive end, so we should've started with the first one. |
| Keith: | Maybe they forgot all about it. |
| Ms. S.: | Possible. And these guys said they were all the same. Twelve, twelve, twelve [for three bulbs]. Fifteen, fifteen [for two bulbs]. And how about this row? |
| Keith: | Well that had more power [the group whose result he is considering had used a six-volt flashlight battery], so it just zips through and then it just gives the power that you need. |
| Ms. S.: | Okay. |
| Keith: | So if the battery.... When it's full power, it's full power until it's a quarter of the way done. You can use it as full power until it's a quarter of the way done, and then you know what's the difference. |
| Ms. S.: | Okay. |
| Keith: | It's slowing down, because then there's probably hardly any power left - a quarter of it - and it starts using the rest. Not enough to feed all through. (Battery Interview, April 1) |

Although some of Keith's concerns were legitimate, his unwillingness to consider that his own idea might have been wrong is quite apparent. Ideally, the controversial test results should have been redone for the sake of accuracy and consistency in reporting methods, but time constraints made this impractical.

#### 4.3.4.3.3. Level 3: Systematic pattern analysis.

At Level 3, students give equal consideration to evidence and counter-evidence. Samantha's circuit explanations were much more consistent with the observed results than were Keith's. Her explanations took into account results from all of the groups, and she spontaneously noted anomalies in the data and took into account possible errors in measurement. She explained the three circuits as follows:

> I think Rebecca style [series] worked well. All of the bulb's got dimmer as they added more bulbs. From 1 light bulb to 2, there was a noticable diff. for RCM [Robert, Carl, Matthew] and JA [Jennifer and Andrea]. For SRK [Samantha, Rachel, Keith] and RJF [Rebecca, Jordan, Frank] there was only a small diff. The bulb's in Rebecca style seem to dim rapidly as you add more bulb's There a huge diff. From 1 bulb to 5 bulb's for every group.
>
> I think that Carl style [parallel circuit with shared connecting wires] #'s didn't drop as rapidly as Rebecca style does. There is a big and small diff. between the 1 bulb and the 5 bulb's. There seem's to be lots of #'s that are bigger than the first # [which she had identified earlier as anomalous because they were "Out Numbered: Higher or way lower than the nuber that you started out with"].
>
> I think that Samantha Style #'s didn't drop as much as Rebecca style #'s did. There also seem's to be #'s that are bigger than the first #. The #'s seem to all be small diff. from 1 bulb to 5 bulb's. All exept for SRK group. But, I think that that is a mistake. The #14 to the #6 is a big diff. All of the other #'s in the group are just a small diff. from 14. (Journal Entry, March 6)

Although Samantha also cited error in measurement as a means of eliminating results that did not support her theory, her explanation more consistently accounts for the broader patterns evident in the results. The tendency to consider all evidence carefully has clear connections to the Level 2 IE emphasis on developing explanations with broad explanatory power.

#### 4.3.4.3.4. Level 4: Alternate interpretations: Causation vs. correlation.

Although a Level 4 approaches to data analysis was not observed, it is reasonable to expect that the ability to consider alternate interpretations of observed patterns could develop once an understanding of the need to seek patterns in the data has been achieved at Level 3. There is a clear relationship between the ability to consider alternate interpretations for observed patterns and the ability to identify variables that may affect a test. For example, heat can cause both evaporation and increased dissolving. Rapidly boiling water in an attempt to test the amount of solute that could be dissolved in the water would be affected not only by the heat but also by the diminishing volume of water. The ability to consider alternative explanations based on stimuli that may have multiple effects forms the basis of a hypothesized Level 4 category for data analysis.

### 4.3.5. Communication: Negotiating meaning.

> *The expression "shared meaning" is misleading. Your meaning and another's are at best compatible; in a given situation, neither reacts in a way that the other could not expect. One only has to get into a discussion of philosophy to realize just how tenuous this compatibility is on the level of abstract concepts. It usually takes a long evening and a good deal of patience before one gets even a vague idea of what the other is trying to say. In a research team, for example, it can take well over a year to establish a workable compatibility with regard to the main terms that are being used. This is what we have called the generation of a consensual domain.*
>
> (von Glaserfeld, 1993, p. 32)

Much has already been said on the nature of the communication that took place during the students' interactions over the course of this study. Communicative strategies identified by the students were highlighted in the discussion of the developing classroom context in Section 4.2.2.2. In the current discussion, I directly challenge skeptical views regarding students' ability to engage in academic controversy, provide evidence of useful strategies displayed in the context of student arguments, and attempt to delineate levels of communication skill.

Linn and Burbules (1993) expressed several concerns regarding the effectiveness of group discussion for helping the knowledge-construction process:

> 1. Janis argues that often the norms and expectations in a decision-making group can limit the alternatives considered, reinforce excessive risk taking, lead to selective bias in evaluating evidence, and support hasty, unreflective decision making. (p. 94)
>
> 2. In generating a prediction, students often prefer to accept the first idea generated, instead of coming up with several ideas then choosing the best. Our interviews with students who did not contribute often reveal that the student felt pressure from the group to move along rather than consider alternatives. Often, the idea generated by the student with the greatest status is the one selected.... Even if a student voices dissent, the group often embarrasses the individual into agreement by sarcasm or by invoking status differences. (pp. 94-95)
>
> 3. ...since group learning is usually unfamiliar to students, they may lack discourse strategies effective for discussion of scientific ideas. In particular, students' everyday discourse strategies are inappropriate for making inferences about conflicting evidence in scientific domains and their models of academic discourse are often incomplete.... Students follow a set of implicit principles that result in few controversies. (p. 95)
>
> 4. ...teachers and textbooks generally model the process of asserting information on the basis of authority. As Forman (in press) demonstrates, this authority-based form of discourse leads to dysfunctional scientific discussions where students assert ideas but do not provide explanations. (p. 96)
>
> 5. ...the goal of respecting others conflicts with the goal of accomplishing the best project...good student leaders often go for compromise, thereby making sure that all the ideas are represented but not reaching the most ideal conclusion. (p. 103)

Caravita and Halldén's (1994) skepticism regarding the availability of "shared goals, recognized distributed expertise, credibility to be gained, need of the others' support, different legitimate modalities for communication, and a group identity" (p. 93) in the science classroom are compatible with these claims.

Linn and Burbules (1993) contrasted their concerns regarding student discourse with the following claim:

> ...the history and sociology of science reveal processes of inquiry that are contextual, provisional, and imperfect; scientific discovery and theoretical development happen, as Kuhn, Lakatos, and others have shown, largely via the social interactions of communities of scientific investigation, not through bursts of brilliance by isolated "great individuals." (p. 105)

If this is the case, their complaint that "teachers may spend all their available time just imparting social skills and have no time left for cognitive activities" (p. 104) is not valid. The social skills that are part of scientific debate are every bit as important to scientific practice as the often improperly emphasized empirical process skills. As was shown in Section 4.2, the students reflected upon many social factors in their discussion of factors that helped and did not help the development of ideas and arguments during class discussion. They clearly understood that their manner of communication was very important to the manner in which their ideas developed, and their ongoing reflections demonstrate their growing understanding of how to take part effectively in group discussions.

The first two points in Linn and Burbules' (1993) list appear to be based on the assumption that consensus must be reached. When students are free to build their own ideas, they need not feel pressured to conform to the ideas of those seen as the brightest or most dominant. Far from limiting the alternatives considered, discourse among students in this study led to the identification of very diverse alternatives that sparked very animated debates throughout both the electricity and the chemistry units. In response to the third point, the students in this study reflected upon their discourse strategies in a manner that helped them to move beyond such obstacles, and they learned to discuss scientific ideas very effectively. Furthermore, the lively debates which typified the discussions in which the students in this study engaged certainly do not support the claim that student discourse strategies result in "few controversies." For the most part, the students' debates demonstrated a remarkable amount of maturity both in the manner that the students were able to challenge each other's ideas and in the manner in which they were able to accept similar challenges to their own ideas. Respecting others does not mean that you cannot argue with them, and the students in this study understood this distinction well. In most instances, their ability to calmly and pointedly discuss academic matters demonstrated a very mature respect for others' ideas and questions. As was documented in Section 4.2, several students explicitly articulated the belief that argument helped to bring out more ideas. Finally, there is no reason why teachers and textbooks need to model authoritarian views. The teacher can model the process of academic discourse, offering and accepting arguments just as the students do. This is discussed in considerable detail in Section 4.4.4. Furthermore, students can and should be encouraged to question the information they read in books. "But why does that happen?" is a common question used by students to challenge their peers' ideas, and is one that could certainly be extended to most textual references. "What do you mean by…?" is also a very common question during student discussion. Students who learn to question books in a similar manner could gain far greater insights than those who simply skim over or memorize what is printed. A detailed example of student interactions with textual information is provided in Appendix G.2.

In many ways, the levels of communication presented in this section appear to be rooted in levels of understanding of the nature of the process by which knowledge is constructed. As was the case in some of the empirical skill categories, much of this categorization is hypothetical. Level 1 reflects the egocentric view that those who are unable to comprehend what it is that he or she is attempting to say are simply wrong. Arguments that seem incomprehensible are likewise viewed as inherently faulty. Level 2 involves the appreciation of others' ideas and of the power of diverse argument to bring out new ideas. Level 3 becomes evident as students attempt to think with others' theories in attempts to communicate in a common language. Finally, Level 4 is based on an understanding that explanations or words that appear to be used in a manner common to two or more people may not denote common interpretations.

#### 4.3.5.1. Level 1: Egocentrism.

Although not observed in this study, the idea of egocentric communication is based on the Piagetian notion of a child who is unaware that views other than his or her own even exist. Until this is recognized, such views cannot be considered. It seems plausible that once egocentric views have been challenged enough times, a more generalized understanding of the potential for alternate views could emerge. Only then can the value of argument, which is explicitly recognized at Level 2, become apparent.

#### 4.3.5.2. Level 2: Sincere consideration of alternate views.

If students are to effectively engage in discussions about their ideas, they need to develop compatible meaning by working patiently with each other to achieve real understanding of what others are trying to say. This involves both sincere consideration of others' questions and sincere attempts to understand what others are saying. In the following excerpt, despite Robert's almost accusing tone, Frank's patient response and continued efforts to explain his idea indicate that he has acknowledged the importance of Robert's question:

> Frank: Okay, so I know that now. Okay, you said, "How does it mix," right? It mixes because the carbonate is trying to kill off the acid, right, or something?
>
> Robert: Why would it be trying to kill off the acid. And when it's finished, uh.... If you put baking soda in the vinegar, it seems the baking soda is dissolved in the vinegar rather than the vinegar turning into a solid.
>
> Frank: Will you say that again, please?
>
> Robert: If you've got a vinegar here and a baking soda, and if you dump the vinegar into the baking soda, the baking soda disappears rather than the baking soda eating the vinegar. The vinegar is eating the baking soda.
>
> Frank: Yeah, that's because the vinegar is a liquid, right, and the baking soda isn't, and that's what causes the gases when the baking soda tries to kill that.... That's what causes the gases. And also, liquids seem to bake into dry stuff, right? (Class Discussion, April 20)

Rachel and Rebecca modeled the use of sincere questions and responses in the following segment from a discussion early in the electricity unit:

> Rachel: What are those two wires on.... What is, um...this wire for?
>
> Rebecca: That wire is connecting the last light on the end.
>
> Rachel: But what does it do?
>
> Rebecca: It's coming from there, and it's touching so it'll light.
>
> Ms. S: Keep asking.
>
> Rachel: Why do you need it?

Rebecca: Well, so it'll light, 'cause it has to touch the side and the bottom of the light.

Ms. S.: You've got some interesting points. Andrea? [to Rachel] Keep thinking. When you've got your question figured out, do ask it, 'cause I think you've got some important questions there. Go ahead, Andrea.

Andrea: Rachel. Do these two wires come in -

Rachel: Okay. This one touches here, and this one goes past here and touches here. Okay, this wire is just touching that.

Andrea: Okay.

Ms. S: There's a thing you can do to show that they aren't touching. Like this and then a thing like this, and that's just showing it jumps the wire. Does that make sense? And then that just means that they aren't touching. And then you can label the ones that are or aren't touching. I might have not done that in the right place, so correct it if I put the thing in the wrong place. So that is touching?

Rachel: Yeah.

Ms. S.: Do you guys see what that little dot means?

Jordan: Yeah. It means it's passed over.

After a brief digression, Rebecca resumed her questioning of Rachel's circuit:

Rachel: Rebecca, I've got another question. What is that wire for?

Rebecca: That wire is coming across the.... It's coming across from this one.

Rachel: But why do you need it?

Rebecca: Well, it'll make the light work.

Ms. S.: But how come? I think she wants to know why will that make the light come on?

Rebecca: Well, it needs to touch the bottom and the side to work, doesn't it? So then it would be like it would only be touching on the side, so it needs that so it'll work.

Ms. S.: [to Rachel] Keep questioning until you're clear.

Rachel: Well, I'm not asking the right question. Does this connect the positive or the negative, or...? What does it carry?

Rebecca: This one is positive, and this one goes into here, 'cause this is the positive and this is the negative.

Rachel: How come this one is touching that and that is touching that and that one isn't touching?

Rebecca: This one's touching this one....

Rachel: No, how come this one's touching that?

Rebecca: The wire's coming from this one, and it's coming over to here.

Rachel: Okay. (Class Discussion, January 6)

Rachel's willingness to take responsibility for asking the right question is quite remarkable. Both her willingness to persist and her very conscious efforts to keep rewording her question to make clear to Rebecca the discrepancy that she perceived clearly demonstrate excellent communication skills.

### 4.3.5.3. Level 3: Thinking with others' theories.

Sometimes, reaching compatible meaning involves adopting someone else's analogy and / or frame of reference. In the dialogue presented below, Robert displayed this strategy both in his use of dragons and ants to make a point and in his ability to switch back to vinegar and baking soda when Frank rejected the dragon analog. This strategy goes beyond argument regarding understanding the applicability of the analogy and is somewhat akin to speaking someone else's language. Robert's understanding of this strategy is likely not generalized, and is therefore provided as a sample of what such dialogue could look like:

Robert: Well, if they're eating stuff...so –

Frank: They're more like dissolving it.

Robert: But then they're not alive. They're not eating -

Frank: No, they're not alive. They're dissolving -

Robert: The vinegar's dissolving it.

Frank: Yeah, but I only said if you put more baking soda in, then the baking soda is dissolving the vinegar. There's not enough vinegar to protect itself.

Robert: How does it protect itself? With a shield?

Frank: No. It protects itself, 'cause if you have more vinegar, then it can take over so, right? 'Cause there's more of it. So it needs more of it to protect it. It's like an army, see -
Class: Yeah, yeah, how does -

Ms. S.: Okay, hey, let's let him finish. He's right in the middle of something.

Frank: Okay, there's a thousand guys here and a hundred guys here, right. So, let's say these guys come and attack first, and there's only a hundred of them. So this is a small group, and there's this big group over here, and they just come in and start to ammo, and they're gone, right?

Robert: Well, what if those hundred guys are stronger than those thousand?

Frank: Well, then there's still more guys.

Robert: Yeah, but it doesn't matter. If you've got an army of a hundred and an army of a thousand, and this army of a hundred is of dragons and this is of ants, well then your army of dragons is going to win, right?

Frank: We're not talking about dragons. We're talking about vinegar and baking soda. I'm just using this for an example.

| | |
|---|---|
| Robert: | So, what if you've got a hundred vinegars and a thousand baking sodas, but the vinegar here are stronger than the baking soda over here? |
| Frank: | How can it be when you don't have enough.... So it'll have to.... Okay. (Class Discussion, April 20) |

It is unclear whether Frank accepted Robert's argument or whether he just needed more time to think about it, but the discussion ended here. In any case, Robert's attempts to speak from Frank's vantage point really helped to facilitate effective communication during this discussion.

#### 4.3.5.4. Level 4: Recognition of interpretation bias: "Is your blue the same as my blue?"

Even when a student is willing to adopt the explanatory framework used by another student in an attempt to reason from common ground, there is no guarantee that similar language is representative of similar interpretation of the concepts being discussed. None of the students demonstrated clear evidence of this on a consistent basis. However, the following discussion pertaining to Frank's definition of energy demonstrates considerable insight on Jennifer's part:

| | |
|---|---|
| Robert: | Uh, to argue with Frank's. It says in the dictionary that energy is an active strength or force. Well, Frank's isn't an active strength or force. It's the shocks that are being the force. So then Frank's little balls of whatever pulls the energy, then the energy should be moving them and not the shocks. |
| Jennifer: | Aren't these things like just in our imagination? Does it have to be something out of the dictionary. Like, Frank's energy can look like what he thinks it looks like in his imagination. It doesn't have to be something that's in the dictionary. |
| Ms. S.: | But it needs to work. We do want these to be true, though. The idea is to reach something that is true. Our minds can |

do that. Just because they're our own ideas, doesn't mean they're not true. If we find out that they're false, we need to change them. Right?

Jennifer: Yeah, but we don't need to use, like, the dictionary's thing of energy. We could use our own.

Ms. S.: So, what he's saying is going through here might not be the same thing that the dictionary is talking about?

Jordan: Yeah, like that could be the human energy.

Ms. S.: Oh, so a different kind of energy?

Jennifer: It has to be Frank's energy. (Class Discussion, March 16)

Samantha also recognized this and clearly articulated an understanding of the need for common theoretical ground when discussing acid:

Samantha: Um...another question might be..."What is the acid?" I think we should answer that as a class - as a group, because if we all had different batteries, and it's kind of hard to think of what acid is if we all have different ideas of acid the, like.... One person.... Say my idea is like this, and another person can say, "Well, my idea is like this." And then they can, like, argue with another person, because each person has a different idea.

Ms. S.: Okay.

Samantha: Or something like that so, like, they could say well thing of energy if right, or acid is right, so we should maybe figure out what acid is and energy is and stuff in our batteries. (Battery Interview, March 30)

It is unlikely that either Samantha or Jennifer had developed a generalized understanding of Level 4 communicative strategy. However, their comments are insightful and could provide effective bases for reflection that might help them to apply their skills more systematically.

## 4.4. The Role of the Teacher

> *...What sorts of teaching techniques are important in supporting a student's construction of his or her understanding? Perhaps first and foremost, the phenomenon students are asked to think about needs to be interesting, worthy of engaging their time and attention. In addition, it should offer a variety of avenues for exploration, various routes of approach. Once these parameters are established, the teacher needs to listen carefully to students' interpretations of the data, paying particular attention to any individual's conundrums, puzzlements, confusions. And the teacher equally needs to pay attention to differences of opinion within the class, giving equal respect to each one, for as long as any student still takes it seriously. By focusing on puzzlements and contradictions, the teacher establishes the notion that ideas are complicated and worthy of time and consideration and that each student is capable of formulating interesting ideas. Further, the teacher acknowledges that "not knowing" is a state that is important to live with – the state that most of us are in most of the time.*
>
> (Julyan & Duckworth, 1996, p. 71)

Some of the information contained in this section has been discussed in piecemeal fashion throughout the preceding sections. However, building ideas specific to the teacher's role into a more coherent framework that focuses on my own role in facilitating students' constructions of their own understandings is helpful in making this role more clear. I have identified five major areas in which my actions were helpful: (a) helping students develop and share their ideas, (b) helping students maintain focus on a topic of investigation, (c) helping students develop implications that are useful for testing difficult ideas, (d) providing timely content and procedural information, and (e) encouraging students to reflect upon their own thinking strategies. In many cases, the use of these strategies occurred in response to a specific situation that made its utility apparent. Identifying these areas will allow me to be more cognizant of them in a manner that I hope will help me to use them more effectively and consistently than I did here. Here my own process of reflective abstraction on processes that occur naturally in certain contexts becomes apparent. Throughout the study period, I did make a conscious effort to ensure that my contributions were not viewed as having ultimate authority. This helped to maintain an inquiring attitude that allowed the students to construct their own knowledge.

### 4.4.1. Help students develop and share ideas.

If students are to partake effectively in discussions such as those evident in the many dialogue excerpts presented throughout this study, they need to be interested in the topic of investigation. Given this, they need to feel comfortable and secure with the uncertainty that characterizes the development of new ideas. As they develop their theories, the ability to articulate them clearly to better allow the recognition of similarities and differences between their own ideas and those of others assumes importance. Awareness of the need to challenge both self and others and to accept such challenges from others without offense are very important in this context. An important component of my role in this process was ensuring that each student's ideas were given adequate consideration and respect. In addition, highlighting similarities and differences between different students' ideas appears to have been an important contributing element in encouraging students to challenge existing ideas. It was likely also important that evaluation procedures recognized the importance of partial understandings and the rational evaluation of ideas.

In many cases, understanding students' explanations required assumptions regarding the meanings they intended to convey. In such cases, these assumptions were guided by what Klaassen and Linjse (1996) refer to as the "Principle of Correspondence" (a term they borrow from Davidson): "Assign such meanings to the other's expressions that the other comes out as consistent and a believer of truths (by your own lights)" (p. 130). Such an assumption is not intended to suggest that any meaning can be attributed to the students' words and actions, but to emphasize the importance of a mindset that promotes persistent negotiation of shared meaning rather than assumed inconsistency on the part of the student. The following excerpt from Frank's individual chemistry interview illuminates the importance of this matter:

Ms. S.: Okay, what questions are you looking into now?

Frank: Uh.... I'm trying to find out some more on hydrogen ..

Ms. S.: Like what about hydrogen would you like to find out?

Frank: I want to see what happens to it. So I can get some hydrogen and put it in baking soda

Ms. S.: And why would you do that?

Frank: I don't know. Just to see what happens and maybe... and maybe even try to evac...try to evaporate the hydrogen...hydrogen. I don't know.

Ms. S.: Okay. What do you think the hydrogen looks like? Uh, here's a better question. What do you mean by evaporate the hydrogen?

Frank: Well, like...like evaporating the vinegar.... Like, sit it out, and, I don't know, see what happens.

Ms. S.: What happens when it evaporates, though. When it's sitting out, what happens?

Frank: Well, like, I don't know that. That's what I'm gonna.... I don't know. That's a good question. See what happens when you do that.

Ms. S.: What do you mean when you use the word evaporate? What is it that you're referring to?

Frank: To see if it, like, when vinegar evaporates, it's not as strong of an acid, or the, yeah, or water. When you heat water, the moisture comes out of it, and it gets stuck on the side of the glass.

Ms. S.: The moisture does?

Frank: Uh huh.

Ms. S.: How does it get there?

Frank: The.... 'Cause when you heat it, the air rises out of it.

Ms. S.: And where does the air go?
Frank: The air will go into the air.

Ms. S.: So how does the water get on the sides of the container?

Frank: Well, because when you have a cork in it or it's covered, it'll.... It has nowhere to go, so it sets on the side of the glass where it's colder.

Ms. S.: Um, and how does that make it back...back.... Or how does that make it water there?

Frank: Um [deep in thought]. How does that make it water?

Ms. S.: Like, you said there's water on the sides, right?

Frank: Um.... Well...moisture.

Ms. S.: And how did it get way up there?

Frank: Because when you heat it, the air goes up. Like, it goes up, so it sets on the side of the glass.

Ms. S.: So, what do you mean by air?

Frank: Well, the moisture.

Ms. S.: Is this.... Is this the same as this kind of air around us?

Frank: No.... It's more like...watery air. Like, yeah, watery air.

Ms. S.: Okay. So is it made of air or you mean it's a gas? So is it....

Frank: Sort of like....

Ms. S.: Like air is oxygen and carbon dioxide [and nitrogen]. Is it that, or is it water?

Frank: It's water, more like water.

Ms. S.: Okay. But by.... When you call it air, you just mean that you can't see it?

Frank: Yeah.

Ms. S.: Is that what you mean?

Frank: Uh.... Yeah. Like when something's steaming.

Ms. S.: Uh huh.

Frank: The teapot or something.

Ms. S.: Okay.

Frank: Um. You go out, and then it rises out.

Ms. S.: And what is it that's rising out?

Frank: The steam.

Ms. S.: Okay. And what is steam made of?

Frank: Moisture.

Ms. S.: Okay.

Frank: Water.

Ms. S.: Water, okay. Okay. I understand what you're saying. Okay? (Chemistry Interview, June 5)

Rather than simply assuming Frank's meaning of air was consistent with my own, the negotiation of his meaning of air greatly clarified his statements (likely to both of us). Assuming that he was a "consistent believer of truths" (Klaassen & Lijnse, 1996, p. 129) was necessary to prompt the meaning-negotiation process documented in this excerpt. This was also necessary, but much more difficult, in the analysis of transcripts portraying dialogues in which compatible meanings had not been adequately negotiated during the actual discussions.

When polite argument was modeled and encouraged, the students very quickly saw the effect that it had on the development of their ideas and became quite motivated to argue with one another. Their appreciation of this process was clearly documented in Section 4.2.2.3. When ideas are viewed as a shared construction for which each student plays an important contributing role, there is high motivation to participate. To effect this, the ideas of each student must be treated with high respect and explicitly recognized for their value. When this respect was modeled, the students soon learned to do the same. When children's ideas are genuinely valued and when the students are able to see how their ideas contribute to the larger group's growing understanding, they are further motivated to participate.

Interest in a given topic appears to be partly based upon the prevalence of alternate or vague views that may incite lively debate. The students did not have developed explanations for the phenomena that they investigated in either of the units that comprised this study. As they articulated and elaborated them, discrepancies became apparent and fuelled very lively debates. Differences in views regarding current flow became apparent only when discussion of different circuit-types led students to formulate ideas describing how different circuits function. Once these differences became evident, the students became very motivated to continue discussing and investigating their theories. Debates regarding the vinegar and baking soda reaction were based more upon the elaboration of vague views and challenges to animist explanations.

On their own, most of the children did not articulate their ideas to a degree of specificity that immediately made evident the discrepancies that drove many of their arguments. Encouraging them to do so played an important role in the continued development of their ideas. This was done by means of direct requests for clarification, often with prompts like, "How do you picture it in your mind?", "Could you draw it?", "Can you think of an analogy that would help you to explain it?", or "How would you summarize that idea?"

Asking students to describe the images that they viewed in their mind sometimes prompted the articulation of analogies that helped them to more clearly communicate their ideas. As was shown in Sections 4.3.1.2 and 4.3.1.3, requests for elaboration regarding how and why suggested phenomena would occur were also very important in helping students develop detailed causal explanations.

The usefulness of directly asking what other situations might fit identified salient features of the phenomenon to be explained was more questionable. In the following case, I identified the requirement of "two different things" as a salient feature from which analogs might be generated. Carl had identified fire as a potential analog on a previous occasion, and it is unclear whether my request helped him to generate the analogy to water. In addition, it seems that I was aiming very specifically to elicit the magnet analog and did not give adequate consideration to his suggestion:

> Ms. S.: Well, can you think of other things that require two different things in order to work? Or if they're both the same, it won't, 'cause, um....
>
> Carl: Well, I can think of something that needs three to work.
>
> Ms. S.: What's that?
>
> Carl: Fire. You need oxygen, fuel, and heat to start a fire. If you don't have heat, you don't have a fire. If you don't have fuel, the fire will go out, and if you don't have oxygen, it won't even start. So.... This is confusing.
>
> Ms. S.: So, on the oxygen, fire, heat thing, why do you need all three?

Carl: Well, fuel is something that will burn, so once you have a fire started, you need fuel to keep it going, and you need heat to start the fire. Friction. You need oxygen, 'cause the fuel burns oxygen. The fire will burn oxygen when it's going. And I don't know why it needs all three.

Ms. S.: Can you think of anything else then that would require more than one?

Carl: Um.... Water? Hydrogen and oxygen.

Ms. S.: What about them? Oh, you need both of those things to make water?

Carl: Yeah. Um....

Ms. S.: Can you think of anything else where you have...it behaves differently if you have two the same and not differently if you have two different? Or differently if you have two the same or if there's two different?

Carl: Um.... I don't know.

Ms. S.: What about a magnet?

Carl: Yeah. That would work, sort of. If you take two of the same sides and put them together, they'll repel. If you take two different sides and put them together, they'll go together. And that I don't know why, either. (Battery Interview, March 25)

At this point, I did not fully realize the potential of Carl's fire or water analogs. I briefly encouraged him to articulate his understanding of these situations, but did not encourage him to relate them back to the battery puzzle. His understanding of these processes appears limited, but may have led to fruitful questions. Encouraging strategies that may have helped him to evaluate and build upon the analogs that he suggested would have been preferable to my direct suggestion of the magnet analog.

The importance of summarizing ideas was discussed in Section 4.3.3.2.1. Summaries provided at my request may be an important bridge to more independent use of this strategy.

Had I provided more direct encouragement to students to reflect upon the usefulness of this strategy, they may have made more conscious and consistent use of it.

Even once ideas were more clearly articulated, the students did not always immediately see the ways in which their ideas clashed with or built upon those of others. Helping them to make these connections evident contributed greatly to student engagement in debate. This was likely because building these connections made evident ideas that needed be debated and because doing so helped to make apparent the continued usefulness of individual students' ideas in the group's construction of theories. At times, this was as simple as asking questions like, "How does that fit with Frank's idea?" or, "Frank, what do you think of that?" Recognition of student ownership of particular ideas (e.g. "Keith's packing theory," "Samantha-style circuits") may have further contributed to the students' feeling that their ideas made real contributions to the development of shared understanding. Teacher intervention was also important to ensure that students gave fair consideration to ideas for which they initially had little patience or to peers who were timid and somewhat hesitant to share their ideas or to persist in questioning. In the analysis of the transcripts of class discussions, it became apparent that I often missed important opportunities to point out similarities and differences between student ideas. Making a more conscious effort to summarize arguments and emphasize similarities and differences between ideas could have been done in the ways that follow.

Sometimes the ideas developed during class discussion did not fully make sense to students who had not yet asked the questions or recognized the discrepancies that prompted the proposal of those ideas. It may have been helpful to ensure that these discrepancies were more obvious by questioning the student proposing a certain idea regarding the motivation for that idea. As it was, connections to these arguments sometimes became apparent only when the students were directly questioned on their own batteries using arguments already discussed at length in the context of other students' theories. During Samantha's individual battery interview, it became apparent that she had not considered several arguments already presented during previous class discussions. These arguments and applicable segments of her interview are presented here.

During a class discussion about three weeks prior to Samantha's interview, Robert argued against the idea of a battery with one side full of energy (+) and one empty side (-) by pointing out that if that were the case, a wire from the positive terminal of one battery to the negative terminal of another should light a bulb (see Figure 2).

Matthew affirmed that he had already tried this arrangement and that it did not work. Keith suggested that the reason it does not work could be that there is not enough room in the other battery. When two batteries are used, he suggested, nothing is leaving to make room for the used particles. Rachel indicated agreement with Keith, and suggested that the addition of a wire from the second positive terminal to the second negative terminal should solve the problem of packing current. She added a wire to Robert's diagram (as shown in Figure 3), and suggested that now it shouldn't have to pack. Frank tested both arrangements with a motor that he had at his desk, and announced that Rachel's solution worked, thereby providing support for her theory.

Robert also argued against the two-sided battery by questioning how such a battery would produce brighter lights when two cells were connected in series. He did not see how the new particles from one cell could get through used-particle barriers to add current to the circuit (see Figure 4).

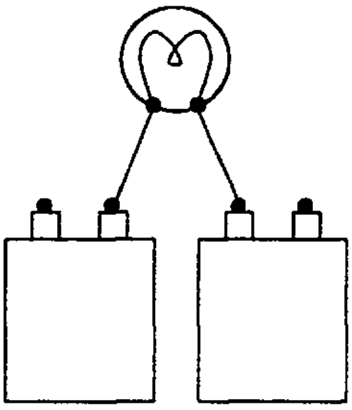


*Figure 2.* **Why doesn't a wire from the positive terminal of one battery to the negative terminal of another cause the bulb to light?**

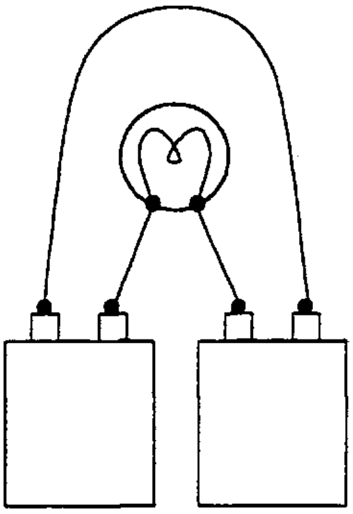


*Figure 3.* **Would the addition of a second wire solve the packing problem?**

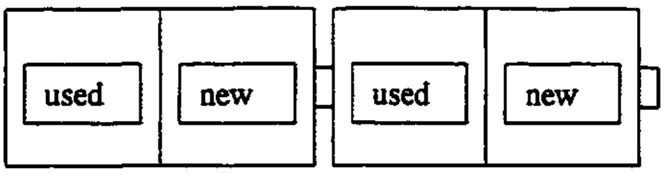


*Figure 4.* **How would a divided C-cell work in series?**

Although Samantha was present for both of these discussions, at the time, they were likely not relevant to the model that she was considering. Had she remembered these arguments, it is quite likely that she would have used them to question her own battery model. She was very conscious about developing a model that people, especially Robert, would not be able to argue against. The discussions about packing current and the inability of new particles to get through the used half of the battery would have been good points to bring up when Samantha described her battery model as follows:

> Samantha: Well, actually, um.... Maybe it's not because there's more bad particles. Maybe this battery is just fuller, like, more full. Like, there would be more particles in it, because it would have all the bad particles and still have the good ones in here. So then as soon as all the good ones.... No, it wouldn't die sooner. The battery would just be more full. (Battery Interview, March 30)

This emphasizes the importance of the teacher remaining very aware of student arguments and how they relate to one another.

The complexity of the arguments used by the students sometimes masked the applicability of familiar arguments. In these cases, I could have done more to help the students organize core features of different theories in a manner that made the advantages and disadvantages of each more apparent. For example, the arguments regarding one vs. two-chambered batteries and one-way vs. two-way current became very complex. Helping the students to summarize arguments for and against each of the following combinations may have helped them put together their arguments in a more meaningful fashion:

1. One-Way Divided: Why doesn't a wire from the positive terminal of one battery to the negative terminal of another light the bulb? If one side of the battery starts out empty, packing shouldn't be a problem. Also, how would two batteries connected in series allow good energy to get through the used side of another?

2. One-Way Undivided: A wire from the positive terminal of one battery to the negative terminal of another should result in packing, because no energy is leaving to make room for the incoming energy. However, this assumes one of two things (unless another alternative can be generated):
    a) Used energy passes through the circuit and returns to the battery via the negative terminal. If so, how does the battery know how much to send to each bulb in series so that each lights with equal intensity?
    b) Friction is created as a particle passes through the circuit and returns to the battery via the negative terminal. If this particle returns unchanged, why does the battery eventually run out?
3. Two-Way Divided: As in (1), a wire from the negative terminal of one battery to the positive terminal of another should light the bulb, and good energy would have to get through the used-energy side of the battery. Also, if crashing positives and negatives light the bulb, how would some get by to light more than one bulb in series? (This led to a whole other series of arguments focusing on the plausibility of tunnels in the wire. These could be summarized in a separate chart.)
4. Two-Way Undivided: As in (1), packing shouldn't be a problem in a two-way undivided circuit. As in (3), it is difficult to explain bulbs in series with this model.

This is much like the instant replay principle discussed in Section 4.3.3.2.1 in that it allows students to reduce complex ideas to a simpler level with which they can work more easily. A more complete summary of the arguments generated by the students is provided in Appendix

D.2. I developed this list primarily to sort out the students' ideas in my own mind, but, after doing so, decided to share it with the class. Having the students develop such a summary would likely have been a much more productive exercise than having them read my summary of their arguments. To generate a summary of this nature, many students would likely have required assistance isolating elements such as packing, series circuits, or used energy that could then have been dealt with individually in the context of each model.

After students became familiar with the trajectory of a given argument, the ability to discuss new arguments in terms of abstractions, each of which encompassed a whole series of arguments, became helpful in incorporating various student arguments into class discussion. Arguments such as, "That's packing" could be used to challenge a model without having to re-develop the whole series of ideas that led to the packing theory in the first place. Having students summarize their arguments and ensuring that all class members understand the nature of the constituent arguments would undoubtedly contribute to the effectiveness of this process.

Sometimes, the entire class failed to consider important alternatives. At these times, the demonstration or explanation of phenomena that could not be explained by student theories became very useful. Awareness of a wide range of discrepant events / arguments known to clash with ideas commonly held by students could contribute to this process. In addition, argument strategies such as extreme-case reasoning and bridging may be effectively modeled and used as a basis for reflection. Students need to learn to provide their own arguments and identify their own discrepancies, but when they fail to challenge themselves or each other, it is important that they be presented with challenges that help them move beyond unquestioned ideas.

Throughout this process, it is very important that the students do not feel that teacher arguments are always aimed at eliciting a correct answer. If students are to question and challenge the information that is presented to them in a manner that helps them to incorporate it into their own knowledge structures, they have to feel comfortable questioning the teacher's ideas just as they would question another student's. I deliberately argued both sides of most arguments and sometimes argued against scientifically accurate conceptions if they were not adequately supported. I believe that this contributed to the students' willingness to argue with me. This idea is consistent with the "Devil's Advocate" stance adopted by Brown and Clement (1989, p. 241) and Clement (in press, p. 9).

The importance of challenging assumptions became very evident when Robert interpreted dissolving vinegar as a chemical reaction and used this to support his theory that all sodium compounds react with vinegar:

> Ms. S.: But does anything with sodium in it react with vinegar?
>
> Robert: Uh, pretty much.
>
> Ms. S.: What about salt? Anybody tried salt with vinegar? Does it react with vinegar?
>
> Robert: When you look at it under the microscope, you can see that it's.... It doesn't go as quickly as baking soda or baking powder, but it does react with the -
>
> Ms. S.: Are you sure it's reacting, or is it dissolving?
>
> Robert: Dissolving or reacting. The way it goes is it's like a "poof," and then a piece of it's gone.
>
> Ms. S.: Is that any different than water and salt?
>
> Robert: I'm going to test that today, too. (Class Discussion, May 15)

He did not find time to test the salt with the water, however, and during the next class period, approached Andrea with, "You said salt doesn't fizz, right?" and proceeded to show her what he had observed with vinegar and salt under the microscope (Field Notes, May 20). He commented on how the crystals changed from square to round. I repeated my suggestion that he try the salt with water.

Helping students develop ways to challenge each other was also an effective strategy. During Samantha's individual chemistry interview, she mentioned having had tested salt and vinegar and noted that it had not fizzed. I asked her how this fit with Robert's sodium theory. The ensuing discussion (presented in Section 4.3.4.1.3) made her very aware of the need to challenge Robert's reasoning, and she did so during the first class period that took place after her interview. In addition to describing an effective way to challenge Robert's assumption about salt and vinegar chemically reacting, Samantha left the interview with high anticipation of the opportunity to challenge Robert's idea during the next class period.

Sometimes unpredictable twists of logic can result in the apparent confirmation of a faulty conjecture. At one point during the chemistry unit, Frank expressed an interest in determining the effect of evaporating vinegar on its effectiveness in the vinegar and baking soda reaction. He claimed that he intended to put evaporated vinegar with baking soda in one dish and regular vinegar with baking soda in another dish in an attempt to see which one was stronger. When I asked him what he expected to see, he indicated that he didn't think the vinegar would be as strong after it was evaporated because the H, C, and O would all evaporate and only the water would be left (Field Notes, May 4). During the next class period, Frank asked me if vinegar could dissolve. When I asked him how he might find out, he suggested checking the Internet. I asked if there were another way, and asked what he meant by "dissolve." He said, "break into tiny pieces," and suggested that he could test the pH of the vinegar before and after heating it to determine whether it dissolved. When I asked if pH changes when something dissolves, he said, "That's another question." I asked how he might find out. He said that he would find the pH of the vinegar before and after. I asked, "What if the vinegar is not dissolved?" He said that the particles would get smaller and therefore weaker if they dissolved and that this would be indicated by a lower resulting pH (Field Notes, May 11). Clearly, his faulty conceptions of both pH and dissolving would have led him to difficulty had he managed to complete this test. If he boiled it long enough, the pH likely would have gone down, but this would have occurred because the already-dissolved vinegar would have become more concentrated, not weaker. In this instance, I needed to help him understand the meaning of the numbers on the pH scale, at least so far as to let him know that lower numbers indicate stronger acids, and perhaps should have discussed other examples of dissolving to help him realize that vinegar is already a solution. This could have been done in a manner that did not completely reject his idea but clarified some faulty definitions that were affecting his reasoning.

Viewing electricity flow in terms of crashing positives and negatives was very popular among the students observed during this study. This misconception has been well-documented in studies of children's understanding of electricity (R. Osborne, 1983; Shipstone, 1984). The students' own arguments led to a fairly early rejection of the "no current in return path" misconception documented by R. Osborne (1983, p. 74), but two-way crashing current proved much more persistent. I tried to ensure that each student at least considered one-way current by encouraging those students with one-way models to share their ideas and by providing arguments in their favor. The following discussion displays an attempt to ensure that the students gave adequate consideration to Andrea's one-way current model:

Andrea: Okay, back to that.... It's almost for everybody. How does your bulb light?

Ms. S.: Well, the crashing ones light, because the energy creates.... Is it like a spark? Or an explosion? What is it that lights when they crash?

Keith: Friction.

Ms. S.: Okay, could you.... Now all of you. Here's a point for all of you. Rather than just trying to argue with her, you can also try to say, "Well how could it work?" because we can't just assume she's wrong just because you have a different one. How could that bulb light? Help think of things. The other you said is friction. Is it possible that this one could have friction?

Keith: I don't know.

Ms. S.: Can you think of a way?

Keith: Well, maybe it can pass something in the light bulb.

Ms. S.: Pass something like what?

Keith: Like a little piece that's sticking out in the wire. Or in the light bulb wire that you put there. So then it zips past, so the positive electricity goes through into the light bulb, then it passes a little piece of something other than that, and it causes friction, 'cause all of them want to get past at the same time.

Ms. S.: And so they're crashing into stuff inside the bulb?

Keith: They're causing friction on that one piece. 'Cause, like, there's a tunnel here, so then it makes a bump inside the tunnel, so then there's a whole bunch of other ones coming here, so then they cause friction all trying to squeeze through the little space.

Ms. S.: Okay.

Andrea: And this is friction, too. So, when this attracted -

Keith: Friction is something that keeps you on the road.

Robert: Look it up in the dictionary.

Ms. S.: Okay, that too, but Keith, keep.... Finish yours. Friction is something that keeps you on the road.

Keith: It keeps you on the road, like. Friction is something that, like, keeps you down. Or is, like, rubbing.

Ms. S.: Try rubbing your hands together.

Keith: That's friction.

Ms. S.: That's friction. What do you notice?

Keith: It gets hot. That's why it lights. It's so thin wire in the light bulb that it gets hot and lights.

Ms. S.: Now, try rubbing your hands together really hard.

Rebecca: So, that's maybe why when you have those two sticks, and you rub across like this, and it gets really hot and it sparks.

Ms. S.: Okay, so you can actually start a fire that way, can't you, Rebecca?

Samantha: Like an eraser, when you erase. Like, when you erase, you have to erase really hard for a while, it gets hot. (Class Discussion, March 16)

To find ways to contradict the many discrepancies that the one-way model produced in the minds of the students is not easy. I was able to provide effective arguments against the two-way current view, but in the end, most of the students were unsure of both. This suggests that under the right circumstances, Wong's (1996) concern regarding students who design their own theories becoming increasingly entrenched in their own ways of thinking may be effectively addressed. I believe this is preferable to having them accept one-way current for poorly understood reasons. As the students progress to higher levels of study, the uncertainty that they exhibited at the culmination of this study may prevent them from making common assumptions that promote faulty reasoning about relative current, voltage, and resistance in circuit components (Gentner & Gentner, 1983; Millar & T. King, 1993; Millar, Lim Beh, & Alam, 1993; Saxena, 1992; Shepardson & Moje, 1994). It is my hope that they will approach further learning regarding electrical circuits in a manner that does not assume the prevalence of one model over the other.

Rather than allowing the students to continue their attempts to resolve the discrepancies associated with the particular model that they favored, by the end of the unit, it may have been useful to help them generate an alternative model(s) that could have helped to resolve the difficulties they were experiencing. By this point, they were asking many important questions, and many of the arguments that they had articulated could have been very helpful in generating a scientifically accurate conception of current flow. The packing theory developed by Keith and Rachel to explain why hooking up the positive terminal of one battery to the negative terminal of another does not result in a flow of current is actually very useful. They just needed a mechanism to explain why such packing would occur and how it could do so without implicating a perpetually charged battery. The timely presentation of information is further discussed in Section 4.4.4.

For students to feel comfortable with the uncertainty that characterizes the process of knowledge construction characterized here, evaluation criteria must be based upon reasoning processes and not solely upon right and wrong answers. As the students reflected on the quality of various arguments, they were able to identify factors that exemplify quality reasoning. By doing so, they not only became more aware of what was important, but were also able to approach their debates with an enthusiasm that was unburdened by the perceived threat that can be inherent in not knowing.

### 4.4.2. Help maintain focus.

As the students became increasingly familiar with the nature of the discussion that characterized this study, they began to recognize their own tendency to drift from the focus that initially drove certain discussions. However, sometimes they needed reminders to stay on topic. Some aspects of focus are very closely related to the FOI framework discussed in Section 4.3.1 and the AR framework discussed in Section 4.3.2.

The following discussion followed a lengthy attempt by Jennifer to explain why vinegar and baking soda react. Prior to the dialogue presented in the excerpt below, Jennifer had commented that if too much of the gas were made, it would make you sick. Although this comment was primarily an aside with no apparent relationship to the nature of her theory, Jordan's questions focused specifically on this aspect of her explanation and diverted attention from the main point of the discussion:

Andrea: Why do you call the gas "strange"?

Jennifer: Well...um. We don't really know what it is, so it could be strange, couldn't it? Like if you didn't know what it was, and you said it's a gas, you wouldn't know that it's strange or not, would you? That doesn't sound right! Can I get back to you? Okay. Jordan?

Jordan: What makes you sick?

Jennifer: Pardon me?

Jordan: You said that it makes you sick if you -

Jennifer: It could make you sick if you had the door and all the windows closed. Everything in here is pretty much solid. It can't seep through it, right? It can't seep through the balloon, right? And if you had this whole floor covered in baking soda, like, this thick, and you pour lots and lots and lots of vinegar to cover this whole floor. And there's too much gas in here, and you could get sick.

Carl: You'd die, because it's $CO_2$. You need oxygen, not carbon dioxide.

Robert: How do you know it's $CO_2$?

Carl: 'Cause that's what it is. Believe me.

Robert: How do you know?

Jennifer: Well, if you're, like, smarter than some people, you'd run out the door, right?

Jordan: So who are you criticizing there?

Jennifer: I don't know. Let's just say Santa Claus is stupid, okay? No person in here is Santa Claus, I hope. Okay, so Santa Claus would stay here not knowing what to do, right? But all of you would run to the door.

Robert: So if the U.S. army or the Canadian army went and dropped a bomb on a country, one bomb of baking soda and one bomb of vinegar, it would kill the whole city?

Samantha: She said that if you had the whole floor full, and it was this thick, and then you pour a whole bunch of vinegar on it, and we all stayed in here, and it filled up the room with gas, and everything is closed and everything, she said that it's going to take a lot, lot, lot of gas.

Ms. S.: Hey guys. I'm going to interrupt you for a moment. This is a very interesting discussion. What's our question?

Class: What is gas? What's making them sick?

Ms. S.: Isn't it "How do baking soda and vinegar make gas?" I mean, it's interesting and it's related, but is this discussion helping to answer our question of how baking soda and vinegar make gas?

Class: No.

Ms. S.: Okay, you guys can do this, too. This time I'm going to say "Hey, are we on track?" but you guys can notice that in your own discussions as well, okay? Go ahead. (Class Discussion, April 22)

Clearly, as the discussion diverged to a consideration of why the gas would make you sick, the question regarding how the gas could have escaped from the vinegar and baking soda was lost. The dialogue did bring out some important points about the properties of the gas, but at this point, the determination of these properties was not something that the students had identified as important. The trajectory of the discussion became a diversion from the main point of their investigation. As the students reflected on how they were sometimes led off track, they commented that references to movies were particularly prone to divert attention from the main point of discussion and became more sensitive to this tendency. If they were guided to reflect on the more subtle sources of diversion evident in the discussion presented here, it is likely that they would be similarly attuned to these types of instances.

There are times when it is helpful to refrain from arguing against a premise or against the accuracy of a proposed source analog until the entire argument has been heard. Sometimes the whole argument is clearly irrelevant, and a SWIID argument can be used to avoid lengthy debate of an irrelevant argument. This requires an explicit understanding of the logic of premises and implications and may be difficult for students to identify, especially when they are new to this type of activity. In cases such as these, teacher intervention is helpful in maintaining a productive line of discussion. In the following case, the argument regarding whether "everything has its own smell" was irrelevant to whether the smell of the vinegar and baking soda changes as the reaction takes place:

Jennifer: Okay. Now we're trying to know what the gas is, right? Now everybody knows what vinegar smells like, right? It smells pretty gross. And everything has its own smell. You don't even have to smell it, but it has its own smell. So, you can't really smell the baking soda smell, but it has a smell.

Jordan: Well, how do you know what its smell is?

Jennifer: 'Cause everything does. Everything has one of the five senses. You can see, you can touch, you can hear, you can smell. Whatever they are. So it doesn't matter if you can't smell it. It already has a smell. It has its own special smell. Flour has its own smell. Sugar has its own smell.

Jordan: You can't smell air.

Ms. S.: Let's hear the point she's trying to make.

Jennifer: So, the strange gas is when you mix the two together. So, you can't really smell the baking soda smell, but you can smell the vinegar smell. So, when you mix the two together, well, you don't smell as much as vinegar, but it probably smells more dry, and you can't tell that, but even though it's sticking together like mud, it still smells dry like flour. Smell it. Okay, Jordan. What do you think about it?

Jordan: It stinks.

Jennifer: Could you smell much of the vinegar?

Jordan: No.

Jennifer: It smells just like play-dough. (Class Discussion, April 22)

Here, I attempted to keep the discussion moving by focusing on Jennifer's argument rather than on whether everything has its own smell. It is possible that her argument would have worked with or without consensus on this matter, but this could only be determined after hearing what it was that she was trying to say.

Similar issues may occur during discussions regarding understanding of source analogs. Simply narrowing the broad generalization that all fire needs friction used as a premise in Carl's match-head analogy would have allowed the continued development of his argument. Instead, a lengthy argument regarding whether friction is really necessary to ignite all fires ensued. This was not necessary for the intended consideration of both fire and chemical reactions as phenomena that are caused by two things. If the students could have agreed on the premise that "friction is responsible for starting some fires," they could have continued the evaluation of Carl's analogy on this basis. He could have simply argued that a chemical reaction is like a fire that is started by friction and thereby diverted the focus of the argument back toward the point he was trying to make. This is an instance in which I should have intervened, asked the students to reflect upon the point of their arguments, and helped to divert the discussion accordingly. Being aware of this as a common point of departure from focus on a given argument will undoubtedly help me to be more alert to it in the future and will allow me to encourage student reflection on the effect that this type of argument has on their arguments.

### 4.4.3. Help students develop ways to test difficult theories.

As was discussed in Section 4.3.3, the students in this study often had difficulty finding ways to test their theories. Teacher assistance is critical at these times. Seeing ways that more of their own theories are testable via the development of observable implications could help students to gain confidence in the process of theory-building and testing. As they are encouraged to reflect on the role of implications in making their ideas testable, they may become more able to generate their own implications. Even if the teacher is involved in helping to generate implications, it is critical that the students take an active role in determining their relevance to the problem being investigated. Implications must be viewed as such for them to be effective.

During the chemistry unit, Jennifer suggested that the reason the baking soda and vinegar reacted could be that they were both positive and therefore repelled each other. However, she did not test this idea, and went on to other activities. Clearly, this is not an easy idea to test. Neither is it impossible. One way of testing the idea could have emerged as an extension of an activity that Jennifer invented during the electricity unit:

Ms. S.: How do they know which one to go to [how do the marbles know which is the negative tunnel and which is the positive tunnel]?

Robert: Maybe the tunnels are magnetic.

Ms. S.: Maybe the tunnels are magnetic! Okay. Oh, and Jennifer's got magnets, too. Okay. So, if it goes one way....

Rebecca: I've got something for Jennifer's. Okay, both sides. It's like a positive and a negative like a battery. The positive and the positive can't touch each other and get a.... They always go a different way....

Ms. S.: Like two positive ends....

Rebecca: And negatives and negatives, they can't touch each other, so it has to be a positive and a negative.

Jennifer: See [showing the class].

Ms. S.: Okay, according to what Rebecca said, if you have to have a positive and a negative to make them go together, wouldn't you want the tunnels to be positive and negative? Like, if you had one tunnel for positive and one tunnel for negative, is anything going to go? (Class Discussion, March 16)

This discussion continued later in the class period:

Jennifer: I just found something out with the magnets. Okay. On the magnets, I named this side A and this side B. Okay? And I found out if you take a side A and a side A, they will push apart. You can't push them together. But if you take a side A and a side B, they'll go together.

Samantha: What about side B and side B?

Jennifer: Side B and side B is the same thing. They won't work.

Rebecca: So, that's like a negative and a negative and a positive and a positive.

Carl: Maybe, wires are backwards. Maybe positive attracts positive and negative attracts negative. Maybe the wires are opposite of batteries.

Ms. S.: Okay, maybe if it's a totally different force. What Robert suggested is that it is a magnetic force. If it is a magnetic force, it would behave as a magnet would. If it's a different force, maybe not. And keep in mind, Jennifer just named it A and B. Maybe.... We don't know which side is A and which is B. We would switch the A and B, and then A and B would attract. Right? If you switched A and B on one magnet, the A would attract the B wouldn't it?

Class: Yeah....

Ms. S.: Or sorry. The B would attract the B. If you flipped the tape on one magnet, [Jennifer is doing this on her magnets]. So how do you know which side is which? There is a way to find out, by the way. You need three magnets to do it. Okay, Jordan?

Using the same principle, Jennifer could have tested various substances with vinegar. According to her theory, those that react with baking soda should have the same charge as vinegar. With this information, she could then have used this procedure with vinegar to determine which substances have the same charge as baking soda. Again, according to her theory, those that react should have the same charge as baking soda. Furthermore, any substances with unlike charges should also react. The existence of neutral substances may have confused this process, but with some guidance, she would likely have been able to recognize that some of the substances react with neither vinegar nor baking soda. This could have been related to the magnet analog by considering the interaction of a regular rock with her magnets. Of course, Jennifer's thoughts and ideas would have influenced the direction of this seemingly logical progression, but my point here is simply that there are often practical and concrete methods that students may use to test seemingly obscure ideas.

The next example clearly illustrates the importance of student-acceptance of implications that the teacher suggests. I attempted to help the students develop a way to weigh hypothetical energy particles to determine whether heat has mass, but the implications of my argument were not entirely convincing to the students. At least some of them believed that even if the energy did have mass, the weight of that mass would not be apparent with equipment available in the school:

Ms. S.: ...If energy is a particle - If energy is a thing, something with more energy should what?

Keith: Have more of the particles.

Ms. S.: And if it has more of the particles in it, should it weigh more?

Keith: Yeah, but it would be so.... The particles are so small that you can't notice the difference.

Ms. S.: Even if it has a lot, lot, lot of energy, and it has a whole lot, lot, lot of particles in it? Would you notice the difference?

Samantha: Well I guess, um.... Like, if you take a feather, and you take a book. Both of them have air particles in them. Like they're both made of atoms, but the feather is made of less atoms.

Robert: But they're not of equal size.

Ms. S.: Okay, keep going Samantha.

Samantha: Well if, like.... Robert had a point there.

Rachel: They're made of different kinds of atoms, maybe.

Ms. S.: But even though it's only atoms, can we notice a difference? Atoms are so tiny that they don't, but if something has less atoms, do we notice that it weighs less?

Robert: Yeah.

Ms. S.: If I took half a block of cheese and a full block of cheese, which one has more atoms?

Samantha: The full block of cheese.

Ms. S.: Which one weighs more?

Class: The full block of cheese.

Robert: The full block of cheese has more cheese.

Ms. S.: Well what's cheese made of?

Matthew: Milk.

Ms. S.: What's milk made of?

Matthew / Robert: Cows.

Ms. S.: Is cheese not made of atoms?
Robert: Yes, but when you've got a heavier amount of cheese, then -

Keith: But that's zillions of -

Ms. S.: Okay, sorry Robert, can you finish?

Robert: If you have this much cheese, or you have half as much cheese, for sure this one is going to be heavier, because there's twice as much cheese.

Ms. S.: So isn't there also twice as many atoms?

Class: Yeah.

Carl: Unless the one is -

Ms. S.: So let's say I have something that has.... Would you agree that heat is energy? Is heat a type of energy?

Class: Yeah.

Ms. S.: So then if I take two identical pieces of metal, one is cold – super, super, super cold, and one of them is super, super, super hot...-

Samantha: So one is Pluto, and one is the sun.

Ms. S.: But they wouldn't be the same size. But if you take two, and they're - Are you all with me? So there's two the same size, but one is super cold and one is super hot. According to the...the energy-is-a-particle theory, which one should weigh more?

Rachel: The hot one.

Keith: The cold one.

Jordan: No.

Ms. S.: If energy is a particle, which one's got more energy in it, the hot one or the cold one?

Class: Hot.

Ms. S.: If heat is energy, the hot one should have more energy in it, right?

Class: Yeah.

Ms. S.: And if energy is a particle, which one should weigh more?

Class: The hot one.

Jordan: The cold one.

Ms. S.: Why the cold one? If heat is a particle.... Here's your blocks, and this one's cold, so it doesn't have any energy particles in it. This one's plum full of energy particles, so which one weighs more?

Class: The hot.

Carl: It should weigh more.

Matthew: Then they'd have to weigh an electron first and then, uh, weigh the other ones.

Ms. S.: Okay. Well, why would we have to weigh an electron, Matthew?

Matthew: Because if you're going to see which one's heavier, then you're going to have to, because if, um....

Ms. S.: Couldn't we just weigh the whole block?

Matthew: No, because that's metal. It weighs itself.

Ms. S.: Yeah, I know. If this block - If they both started exactly the same and this one gained two grams, where did the two grams come from?

Matthew: The heat.

Ms. S.: Do you see what I mean? It's like with a beaker. If you filled a beaker with sand and you only want to know how much the sand weighs, you subtract the weight of the -

Matthew: Beaker.

Ms. S.: So could we just subtract the weight of the block?

Class: Yeah.

Ms. S.: From that other one?

Class: Uh huh.

Ms. S.: So what do you think, would a hot block weigh more than a cold block?

Class: [mixed responses]

Ms. S.: Samantha?

Samantha: It should weigh more than the cold block. But we did a test in science a couple years ago...maybe it was last year. We did the thing with density, remember? The warm stuff was less dense, the cold stuff was more dense. So, if the cold stuff is more dense, according to that theory, then the cold one should be more dense, and the hot one should be less dense.

Ms. S.: Okay. But will it weigh more? So you're saying.... What would make it less dense?

Samantha: If it's more full of particles, then it's going to be dense, right?

Ms. S.: Uh huh.

Samantha: So that should be heavy.

Ms. S.: Careful, though. If it's.... Why do hot things get less dense? Rachel?

Rachel: What we should do to prevent that is, like, maybe stick some kind of plastic over top, because warm stuff evaporates.

Ms. S.: Even if it's metal?

Rachel: I was thinking of water.

Ms. S.: Yeah, water evaporates, but the metal would have to melt first, wouldn't it? [It appears that I missed her point about water.] You have to get it really hot to melt it. But why do hot things become less dense? Is it because they lose particles, or because particles do what? Do you remember?

Rachel: They spread out!

Ms. S.: They spread out, so it would actually.... Are you losing particles, or are they just taking up more space?

Andrea: Taking up more space.

Ms. S.: Should that affect how much they weigh or just how dense they are?

Rachel: How dense they are.

Ms. S.: Okay, Samantha. You looked a little puzzled there.

Samantha: But if.... Then the cold ones.... If they're more dense.... If the hot ones don't lose anything and just spread out, then the cold ones.... Shouldn't the particles be in all one space then, if that's what density is?

Ms. S.: And they crowd together?

Samantha: Shouldn't they be in all one corner or something?

Ms. S.: Okay. You don't notice it as much in a solid, do you? Like when it's cold in the room, do you notice the desks suddenly shrinking?

Class: No.

Ms. S.: But they probably do a little bit, just not enough to notice, right? But does the actual weight of the desk change, or do the pieces just move closer together?

Class: Move closer.

Ms. S.: Like if Andrea stands.... Can you come up here for a minute? If Andrea stands right there, and I stand right here.... If she weighs fifty pounds, and I weigh a hundred pounds, what's our total weight?

Class: A hundred and fifty.

Ms. S.: Now if I stand here, and Andrea stands there, how much do we weigh?

Class: A hundred and fifty.

Ms. S.: Does it matter how close we are, how much we weigh?

Class: No.

Ms. S.: So should it matter in here, how close the particles are to each other, how much they weigh?

Class: No.

Matthew: It depends how much you have.

Ms. S.: Depends how much they have. And if they're spreading out and going closer together, are they losing particles or just changing the amount of space they take up?

Class: Just changing the amount of space. (Class Discussion, April 6)

In this case, although the implications were supposed to be observable, I did not adequately address the students' concern with the negligible weight of energy. Confusion between density and mass further complicated the issue. There is little evidence to suggest, even if heat did have mass, that the comparison of the masses of an object before and after heating would result in a measurable difference. Because I dealt inadequately with the students' concerns, the value of the whole discussion is questionable. If the students do not see the suggested implications as logical outcomes of the phenomena being investigated, "So what if it does?" (SWIID) becomes an appropriate response.

### 4.4.4. Share information and procedures.

> *Now, what should we teach first? Should we teach the* correct *but unfamiliar law with its strange and difficult conceptual ideas, for example the theory of relativity, four-dimensional space-time, and so on? Or should we first teach the simple "constant-mass" law, which is only approximate, but does not involve such difficult ideas? The first is more exciting, more wonderful, and more fun, but the second is easier to get at first, and is a first step to a real understanding of the second idea. This point arises again and again in teaching physics. At different times we shall have to resolve it in different ways, but at each stage it is worth learning what is now known, how accurate it is, how it fits into everything else, and how it may be changed when we learn more.*
>
> (Feynman, 1995, p. 3)

There were many instances throughout the study period during which I presented the students with factual or procedural information, typically in response to specific questions. This students' readiness for this information became apparent when it provided support for or contradicted the arguments they were attempting to make, when it provided a viable alternative to an idea for which significant unanswered questions or discrepancies had been identified, or when an identified implication could be observed by means of a suggested procedure. The students' use of books provides many parallels to information presented directly by the teacher and is therefore also discussed in this section.

Direct requests for information regarding the components of the materials with which the students were working were very common. Questions such as "What is baking soda made of?", "What other substances have carbonate in them?", and "Is there a divider inside a battery?" all reflect questions of this nature. In response to questions such as these, I typically either provided the answer or directed the students to useful reference books. The students often incorporated this information into their theories.

The students typically did not use information presented before they had identified a need for it. In the hope that students would note patterns in the chemical formulas, I presented the class with a list of common acids and bases. Keith likely spoke for many when he said, "Do we have to write this? I'll never use it." (Field Notes, May 15). During Carl's chemistry interview, this information did become relevant in helping him move beyond the belief that there was really no way for him to find out if his theory made sense or not. With guidance, he noted the common "H" atom in the acid list and the common "OH" cluster in the base list, and recognized the possible formation of water if these were put together. This supported his idea that vinegar and baking neutralize one another and kindled his interest in the list of acids and bases.

After Keith and Carl had each developed a detailed model of the vinegar and baking soda reaction, they noted that their explanations were alike except for the type of gas produced: Carl hypothesized that is was $CO_2$, whereas Keith favored NaH. At this point, introducing the boys to the limewater test provided them with a means of testing their ideas. Similarly, when another student predicted the presence of water, I introduced him to cobalt II chloride test paper. The students realized that pH paper provided a measure of acidity, but often misused the color scale. This is an issue that I should have addressed more promptly. The students had identified a need for a measure for acidity, but their faulty method of reading the scale led them to faulty conclusions that could have been easily prevented. Equipment such as filter paper, microscopes, well slides, a triple beam balance, alcohol burners, ring stands, and graduated cylinders were all introduced as needed in the context of particular investigations. In some cases, student-identified needs were based on WWHI questions rather than implications-based investigations, but all equipment and procedures were presented in contextualized settings.

Sometimes a need for information became evident when students attempted to confirm understandings they wanted to use as base analogs. I often did not intervene in these cases, but it appears that doing so may have been helpful. For example, as the students debated the match-head analogy (relating friction and fuel to positive and negative energy), helping them to develop a better understanding of fire so that they could compare it to their understanding of a battery may have been helpful. Fire was used as a source analog for both the battery models and the vinegar and baking soda reaction. In a subsequent class, understanding of fire became critical to an argument for air pressure. Perhaps it would be particularly beneficial to help students develop a clear understanding of certain concepts that recur in a variety of contexts and / or that are often used as source analogs. Understanding fire, magnets, and the nature of life could all be important in this regard.

I have already discussed the possibility that, once the students had identified a wide variety of questions regarding different battery models, it may have been useful for me to present a model that is consistent with a scientific conception of a battery. I did encourage the students to consider one-way current, but I did not directly address the questions they still had about this type of battery. Ideally, there should always be questions remaining at the end of a unit, so I do not think that this was necessary. The importance of deliberately facilitating the development of questions that remain unanswered at the end of a unit of study is discussed briefly in Section 5.1.2.1.

Throughout the chemistry unit, many of the students used printed information as a source of ideas to help them develop theories regarding how vinegar and baking soda react. In the beginning of the unit, many of them persistently sought information regarding what each were made of. Several students were highly influenced by a visual model portraying two molecules of hydrogen combining with two molecules of oxygen to produce two molecules of water. Samantha found support for her idea that chemistry is when things mix to create something new in a list of word equations. Typically, small bits of carefully chosen information from the readings were incorporated into the students' own theories. The emphasis remained on student-constructed knowledge, with text-based information being incorporated into these constructions. Carl aptly summed up the role of books in his statement that "They should [be used], but only if you absolutely need that type of information" (Class Discussion, March 30).

Some may argue that allowing the students to construct their own ideas in this manner could contribute to the development of a view of science that is unable to distinguish between more or less rational ideas. However, the students were not encouraged to believe that any idea is acceptable and were expected to challenge their ideas continually so that their understandings would continue to progress. It could be argued that expecting students to learn static bodies of content without expecting them to challenge the ideas therein would lead to even greater misunderstanding.

Students must deal with approximations that are less developed than the ideas with which the people working at the frontiers of science work with. Expecting them to learn material that answers questions that they have not yet asked or, at the very least, do not yet comprehend, does not allow them to understand this information as more than formalisms.

Students who are expected to develop their own knowledge in the manner suggested here develop incomplete knowledge, but are aware that it is incomplete. Students who are expected to learn intact bodies of established knowledge have incomplete knowledge with no real understanding of its deficiencies. Students need to develop an understanding of science as it is understood by the scientific community. Their own rational and creative processes can allow them to do so in a manner that allows continued interaction with content matter and a much fuller grasp of the transient nature of that knowledge.

In the development of their understandings of electrical circuits and of the vinegar and baking soda reaction, the students did not (and likely could not have) simply read text information to provide complete answers to their questions. An extended dialogue documenting their attempts to make sense of material they were reading as they attempted to develop an understanding of the nature of electrical current is provided in Appendix G.

The use of books, empirical testing, and the students' own imaginations are all incorporated into the theory-generation process. From this perspective, the distinction between a context of development and a context of justification focuses less on a historical vs. ahistorical approach to science education than it does on the manner in which the students construct meaning. In a context of development, students develop new theories by connecting ideas in ways that are personally meaningful. In a context of justification, a theory is given, and the task of the student is to deconstruct it and put it back together in a manner that makes sense to him or her. Either way, the student must construct meaning based on the integration of information gathered from his or her surroundings with the information that already forms the complex webs of ideas within his or mind. As Vosniadou and Brewer (1987) pointed out in their study of children's understanding of the earth and sun, "Children, unlike scientists are often faced with the problem of assimilating into their current cosmology information provided by adults, based on a heliocentric view" (p. 58). To ignore the manner in which children interact with poorly understood representations of scientifically accurate conceptions is to fail to consider important factors that will likely continue to influence the manner in which they build their understandings.

Nadeau and Désautels' (1984) concerns about misconceptions regarding the history of science could also be effectively addressed using the approach to knowledge construction discussed here. It is likely that a classroom context that focuses on students' context of developments could have a powerful impact on improving understanding of the history of science, especially in terms of addressing the misconceptions that "science develops in a linear, logical fashion, rather like the table of contents in a book" and that "advances in science are the results of the periodic efforts of men, and occasionally women, acknowledged to be in the genius category" (Nadeau and Désautels, 1984, p. 63). However, for such transfer to take place, students must see their own work as analogous to that of scientists. If the manner in which Carl's understanding of the fallibility of his own ideas is able to co-exist with his more absolutist beliefs regarding the nature of knowledge developed by scientists is any indication (see Sections 4.3.1.4 and 4.3.3.2.3), transfer may not occur without direct confrontation of student ideas. Even so, that the students have their own experiences to act as a basis for considering the similarities between the two could provide a rich context for reflecting on the development of this understanding. Students who have experienced science firsthand should be much better able to relate to the actual manner in which science developed historically, especially if reflection on personal experiences and the incorporation of contextualized historical examples is a part of the overall framework of discussion.

### 4.4.5. Encourage reflection.

Reflection on effective thought processes is a recurring theme throughout the discussions presented in this paper. To help students identify effective reasoning strategies, the teacher must be able to recognize them and to encourage students to reflect upon and thereby reify them. My own lack of clear understanding regarding effective reasoning strategies prevented me from doing so in many cases. As these have become clearer in my own mind, I have become a much better reflective guide. In several areas, my current class has already gone significantly beyond the understandings developed by the students who participated in this study. Teacher modeling of effective idea-generation and evaluation strategies may also provide argument strategies upon which student reflection could be based.

# V. IMPLICATIONS

If students reasoning is to be effectively promoted in the manner suggested here, critical issues must be addressed within both the development of science curricula and the preparation of science teachers. These issues are the focus of Chapter Five.

## 5.1. Implications for Science Education: Theoretical Anchoring

> *When we read about this in the newspaper, it says "Scientists say this discovery may have importance in the search for a cure for cancer." The paper is only interested in the use of the idea, not the idea itself. Hardly anyone can understand the importance of an idea, it is so remarkable. Except that, possibly, some children catch on. And when a child catches on to an idea like that, we have a scientist. It is too late for them to get the spirit when they are in our universities, so we must attempt to explain these ideas to children.*
>
> (Feynman, 1988, pp. 244-245)

The FOI framework developed in this study outlines a progression of learning that takes place as students become conscious theory-builders. The AR and IE frameworks outline ways in which the theory-building process can be made more rational as students develop more rational approaches to identifying and evaluating new connections between their ideas. This may occur via the processes of mapping and validating analogical relations or through the identification and testing of the implications of new ideas. Each of these processes is dependent upon the development of important metacognitive understandings about the nature of science and about the nature of knowledge. In turn, the development of these understandings necessitates a learning environment in which students are expected to generate supported theoretical understandings and are guided through this process. The successful implementation of such a program is dependent upon both a suitable science curriculum in which goals for skill and content understandings are based on levels of understanding rather than absolute truths and upon teachers who understand the processes involved in learning science. Within this context, students may develop scientific reasoning skills while still being held accountable for basic content understandings.

### 5.1.1. Productive theoretical contexts for elementary classrooms.

> *Gases are too broad and complex a subject to be tackled head-on. The burning-candle experiment provides an approach by a specific and narrow question: "What happens to the air in a jar place down over a burning candle?"*
>
> *Pursuit of this single question lends purpose and interest to the activities. And, just as a scientist often finds that one question leads to others which may require both new thinking and new techniques, so does the initial question in "Gases and Airs" lead the student to consider many pertinent questions in the study of gases.*
>
> (Alberti, Davitt, Ferguson, & Repass, 1974, p. 4)

When students start with a theoretical base, learning may become embedded within that whole. The whole does not remain static, but serves as a temporary framework upon which new knowledge can be built. Although perhaps on a smaller scale, a theoretical base of this nature acts like the paradigms that T. Kuhn (1970) discussed:

> Without commitment to a paradigm there could be no normal science. Furthermore, that commitment must extend to areas and to degrees of precision for which there is no full precedent. If it did not, the paradigm could provide no puzzles that had not already been solved. Besides, it is not only normal science that depends upon commitment to a paradigm. If existing theory binds the scientist only with respect to existing applications, then there can be no surprises, anomalies, or crises. (pp. 101-102)

Matthew made a comment that demonstrates a preliminary understanding of this idea, although he did not directly address the importance of the theories underlying the questions he identified as important: "Um, when we ask questions, everybody gets them, and then they think of questions, and then people get answers from them, and then more people think of questions from the answers, and then the argument goes on again" (Class Discussion, March 24).

The students in this study were not expected to learn a rigid set of facts. Rather, they were expected to ensure that the conclusions that they formed fit together in a logical and consistent manner. As they participated in various investigations, many important questions pushed their understandings to higher levels. For example, as they attempted to construct plausible understandings of the manner in which circuits work, they learned to distinguish between various circuit types, and their questions eventually demonstrated a search for understanding of the very nature of matter and energy. During the chemistry unit, attempts to discern whether the mixture that was once vinegar and baking soda still contained those chemicals, and later to determine what the new substance(s) was, the students learned about various indicators and about how to use the properties of different substances to help identify them. They used smell, taste, crystal structure, reactivity, pH, and gas tests for oxygen, hydrogen, and carbon dioxide in their efforts. In addition, they attempted to separate components for further analysis by means of evaporation, crystallization, and filtration. They also gained experience in using a microscope and other lab equipment. In addition to all of this, the questions that several of the students articulated regarding the nature of the forces binding the atoms of vinegar and baking soda together and the forces causing them to separate and selectively recombine go far beyond traditional expectations for students at this level. The theoretical context in which they worked provided a motivating environment for testing the effects of different circuits and for comparing the properties of different substances that is not evident when similar activities are done for the sake of observation, classification, or learning how to do a fair test.

When learning is approached in this manner, there is no guarantee that the trajectory of students' questions will always necessitate the particular activities in which the students in this study became engaged. However, if curriculum goals are worded broadly, it is likely that by choosing from a set of carefully selected opening questions that are common to children's experiences that these could indeed be met. In some cases, these questions could be stimulated by discrepant events known to provide effective challenges to common student views. It seems likely that investigations based on these questions could entail a core group of content and skill objectives and would still allow students to partake in the dialectic cycle of self-questioning that is so critical to the nature of science. It would be interesting to see how the questions used by the students in this study would be approached by other groups of students.

### 5.1.2. Viewing content knowledge through levels of understanding.

> *It is precisely this problematic approach that marks the true scientific mind. To a scientific mind, all knowledge is an answer to a question. If there has been no question, there can be no scientific knowledge. Nothing is self-evident. Nothing is given. Everything is constructed.*
>
> (G. Bachelard; as cited in Nadeau & Désautels, 1984, p. 77)

The students in this study did not achieve understandings of electricity or chemistry that are fully compatible with current scientific conceptions. However, they developed partial understandings and asked some very insightful questions that could provide a sound basis for the continued development of complex qualitative and quantitative understandings of concepts pertaining to further studies in these and related fields. To better facilitate student progression through the often-predictable levels of understanding evident in their ideas regarding particular topics, it is important to understand these levels, to help students identify effective challenges that can be made to understanding at each, and to base judgments of the students' levels of content understanding on levels of conceptual development rather than on their ability to articulate shallow understandings of conceptions that are consistent with current scientific interpretation.

#### 5.1.2.1. The importance of unanswered questions.

> *Well, it can go on both ["Helped" and "Didn't Help"], 'cause sometimes you think you have it all, but you find out it doesn't work, but then it can be good because you can learn more about it.*
>
> \- Jennifer (Grade Five)

> *That is the way it is in physics. For a long time we will have a rule that works excellently in an overall way, even when we cannot follow the details, and then some time we may discover a* new rule. *From the point of view of basic physics, the most interesting phenomena are of course in the* new *places, the places where the rules do not work – not the places where they* do *work! That is the way in which we discover new rules.... Historically, we have always been able to amalgamate them* [various phenomena of nature], *but as time goes on new things are found. We were amalgamating very well, when all of a sudden x-rays were found. Then we amalgamated some more, and mesons were found. Therefore at any stage of the game, it always looks rather messy. A great deal is amalgamated, but there are always many wires or threads hanging out in all directions.*
>
> (Feynman, 1995, pp. 25-27)

When information forms the answer to an identified question, we perceive it as interesting and it is therefore more likely to become knowledge. Students who wonder how particles separate and recombine will find interest in theories of bonding. Those who have puzzled over how energy can travel through a bulb without being used up, return to an undivided battery, and be unable to be used again are likely to find interest in the chemistry that helps to explain this puzzle. When these topics are dealt with in Junior or Senior High Chemistry, the theoretical frameworks and the catalytic questions that accompany the students' current frameworks should better prepare them to integrate new information. This implicates unanswered questions at the end of a unit as indicative of success rather than as an annoying consequence of time constraints. These questions are what allow continued interest in a topic of inquiry and are ultimately what drive the formation of new knowledge, even at the frontiers of scientific understanding. Clearly, however, this also raises significant challenges to the manner in which content is typically approached in Junior and Senior High, and possibly beyond.

The culmination of the chemistry unit left the students with a partial explanation of the vinegar and baking soda reaction, but many expressed interest in unanswered questions about the manner in which the particles separate and come back together: Why do they separate in the first place? How do the particles know which particles to recombine with? These questions are catalysts that will take the students beyond their current Daltonian views to explore the implications of other atomic models that are better able to provide answers to questions about the nature of bonding. Fortunately, each subsequent model will come with questions of its own. If students are helped to find these questions and encouraged to keep searching for answers to them, their understanding should continue to progress.

Few students will develop scientific conceptions of atomic structure or the behavior of electricity. For most, quantum physics will remain a perpetual mystery. A single person simply cannot acquire complex understanding of all areas of study, any one of which could entail a lifetime of study. However, those who understand the importance of continually seeking deeper levels of why will have a much greater understanding of the scientific enterprise and a much-needed appreciation of its strengths and limitations. For those who do choose to pursue a topic studied in elementary school in greater depth, the basis provided by an approach to learning that encourages the development and continual challenging of theory will help them continue to develop necessary understandings and questions at higher and higher levels.

#### 5.1.2.2. The need for levels-based content assessment.

If students are expected to progress through levels of understanding pertaining to various phenomena, then these levels need to serve as a basis for evaluating their content understandings. Both the understandings that they articulate and the types of questions that they pose could be used to help identify their level of understanding regarding a specific concept. Understanding students' knowledge in this manner would be both a fairer way of assessing what they know and a more useful way of determining how their ideas might be further challenged.

When attempting to determine a child's level of understanding regarding a particular phenomenon, it is very important to ensure that apparent understandings are in fact conceptual understandings and not just memorized facts. According to Vosniadou and Brewer (1992),

> Generative questions have a far greater potential for providing information about children's underlying conceptual structures. These questions ask children to explain phenomena which they cannot directly observe and about which they are not likely to have received any direct instruction. Consider, for example, the question "If you were to walk for many days in a straight line, where would you end up?", "Would you ever reach the end or edge of the earth?" and "Does the earth have an end or an edge?" In order to answer these questions children cannot rely on some unassimilated piece of information they have received from adults. Rather, they need to create a mental representation of the earth which

> includes information about its shape and use this mental representation to provide an answer to the question. (p. 542)

To more effectively assess student progress, teachers could identify common levels of understanding and common puzzles inherent in each. Clearly, assessment of this sort poses significant challenges to traditional forms of standardized achievement testing. It is possible that new tests could be designed to reflect standardized levels of understanding through patterns of responses to "generative questions." These tests would provide a limited view of student learning, but could be an important first step toward more realistic assessment of what the students truly understand. I do not believe that either traditional process skills or the types of thinking skills discussed in this study can be effectively measured by a single performance task or even through a single interview. Conscious, systematic use of a particular strategy is often difficult to identify in an isolated situation.

#### 5.1.2.3. Implications for topics of study.

During the course of this study, certain analogs recurred in several contexts. Understandings regarding fire, magnets, and the nature of life were each salient in at least two different areas. The two topics that were investigated in this study overlapped in many ways, so it is not surprising that common analogs were applicable to both, but their recurrence nevertheless suggests the possibility that the development of certain understandings may provide important underpinnings for understandings in many other areas. If ideas such as these were developed in greater detail, perhaps as central topics of study, they could then provide better sources of explanatory structure in a wide variety of other contexts. This could help to alleviate difficulties such as the one that Carl identified when he claimed that trying to explain how vinegar and baking soda react is like trying explain fire: "You can't." It could also help to prevent the inappropriate transfer of explanatory structure from poorly understood or implicit base analogs. The identification of other analogs that could serve as broad explanatory bases will be important to the effective development of this idea.

In a related vein, providing students with the opportunity to take part in a set of carefully selected concrete experiences may allow them to develop common source analogs in the form of the physical intuitions discussed in Section 4.3.2.1. Clement (1994) offered the following suggestion:

> This allows for the possibility that the construction of intuitions can be fostered by certain experiences in school, making it possible to frame hypotheses such as: "By carrying out suggested experiments with pucks on a frictionless air table, students can develop intuitions about motion in a frictionless environment." (p. 213)

In addition to helping students develop understanding of analogs that may be identified as common to a variety of students, individual students should be encouraged to become familiar with the analogs that drive their own thinking. It seems likely that those developed in one context could easily recur in others. If understanding of these analogs is more clearly developed, the transfer of inaccurate information or the inappropriate transfer of accurate information could conceivably be reduced.

Finally, the importance of articulated understandings of broad patterns and themes may implicate the need to help students reduce certain understandings to broadly applicable generalities. Causal patterns such as positive and negative feedback loops recur in many contexts. It may be possible to help students identify themes of this nature by providing multiple investigative contexts that incorporate these cognitive structures.

As students map the similarities that exist between them, they may come to recognize the more general structure inherent within. Identifying productive themes and investigative contexts that could help to develop important broad-based patterns of understanding is an area that requires a great deal of further research.

### 5.1.3. From traditional process skills to understanding scientific reasoning.

> *Knowing the existence of such logical and rhetorical fallacies rounds out our toolkit. Like all tools, the baloney detection kit can be misused, applied out of context, or even employed as a rote alternative to thinking. But applied judiciously, it can make all the difference in the world – not least in evaluating our own arguments before we present them to others.*
>
> (Sagan, 1996, p. 216)

Throughout this paper, I have identified areas of concern with the manner in which traditional science process skills are often addressed. Skills involving controlled experimentation, measurement and observation, and data analysis remain important, but need to be rooted in a theoretical context, the development of which involves a set of skills that, for the most part, are typically not addressed. These are the skills that form the FOI, AR, and IE frameworks. If these are to assume their necessary place in curriculum and assessment materials, certain issues need to be addressed. One of these is the importance of self-assessment in an evaluative framework that relies so heavily upon reflective practice. Another is a focus on skill levels that necessitate a theoretical context for their attainment.

#### 5.1.3.1. The need for self-assessment.

The frameworks developed in this study could prove very useful in helping students to reflect on their own thinking strategies. As I have already noted, understanding these levels has made me a much more effective reflective guide. It is important, however, that the levels not be simply presented to students. To understand them, they need to construct them through reflection on meaningful scientific activity and discussion. If students are involved in developing rubrics based on what they perceive as important to the development of scientific understanding, they should also gain the control over the evaluation process that they need to feel empowered about their own learning.

#### 5.1.3.2. Understanding transitions between levels.

Henriques (1990) discussed the difficulty of evaluating student performance in a classroom where the students are engaged in diverse activities of their own choosing as a critical obstacle to achieving more constructivist-based classrooms:

> And what about evaluation? What were we going to test? Buy why must we evaluate? Another scandal: How can one conceive of educational practice without evaluation? Yet all the teachers agreed that evaluation was sometimes absurd because one did not assess what one thought one did and wanted to do. They agreed that it served mainly to reassure the parents that teachers were in control of what happened to the children, to reassure teachers that they could judge what their pupils had learned and all this at the expense of the children. For to feel judged constantly makes one insecure, causes stress, teaches one to adopt bad intellectual habits. It is better to learn by rote than to understand, it is better to pretend that one has understood, it is better to cheat than to fail a test, and so on. (p. 182)

I think it is a rather extreme jump to suggest that the problems associated with traditional evaluation procedures imply that evaluation is not necessary at all. Being unable to "assess what one thought one did" demonstrates a flaw in the assessment instruments that are available. Perhaps no evaluation is better than harmful evaluation, but it is certainly possible to meaningfully assess the levels of activity in which students partake. The levels-based framework developed in this study represents an attempt to do just that. When combined with the unique perspectives of each new group of students, an instrument with some degree of consistency that still allows for individuality should be possible. The levels-based frameworks developed here provide important benchmarks for teachers as they observe their students. By clearly understanding the characteristics of students at each level and by understanding the factors that influence progression between the levels, teachers may more effectively guide their students through this process. At the same time, each group of students may conceptualize these ideas in ways that are consistent with, but differ in emphasis, organization, or wording, from those presented here. Without an effective evaluation system that provides a basis for guiding the students through this process, knowing how and when to intervene is not possible.

## 5.2. Implications for Science Teacher Education: Epistemological Understanding

*If there is a key to reinventing our educational system, it lies in what our teachers believe about the nature of knowing.*

(Dykstra, 1996, p. 202)

Much has already been said about the role of the teacher in a context such as the one proposed here. To take up this challenge in an effective manner, teachers must have a clear understanding of the manner in which students construct meaning and of the developmental progressions inherent in foundational content areas.

### 5.2.1. Teachers at Level 4.

Henriques (1990) described one reaction of the teachers in whose classroom she conducted her research as follows: "Seeing the enthusiasm of the children, the teachers were reassured that something positive was happening, although they could not specify what" (p.

179). Although their enthusiasm is a useful first step, realizing that something positive is happening and being able to identify and encourage productive ways of thinking are two different things. The development of these understandings is likely something that needs to take place over an extended period of time. By reflecting on positive (and negative) practices, teachers may reify these and monitor their use in a more systematic way.

To guide reflection on the thinking processes involved in the construction of knowledge in an effective manner, teachers need to understand clearly the processes that are involved in doing so. Partial understanding may be achieved through careful analysis of the words and actions of the children with whom they work. However, true understanding also requires that they become self-reflective learners who consciously construct their own understandings in areas that are new to them. Many people have never been encouraged, at least in a school environment, to do this. To understand the impact of this approach, it must be experienced.

Teachers without a science background (as is often the case in elementary school) often harbor many of the same misconceptions that are common among the students that they teach. They can gain a much deeper understanding of both content and the process by which it is learned by constructing their own understandings of relevant content areas and by reflecting on the manner in which their understanding progresses as they do so (Smith & Neale, 1994; Summers, 1992; Wallace & Louden, 1992).

### 5.2.2. Through the eyes of children.

Teachers need to believe in the powerful ways that students piece together understanding and to seek consistently the logic behind the ways in which they do so. In this manner, their ideas may be truly appreciated and the manner in which they grow may be more fully understood and appreciated. Teacher education programs should involve considerable time listening to and later analyzing the ways in which individual or small groups of students construct understandings.

### 5.2.3. Redefining "prepared for class."

Teachers need to understand the levels of understanding that students progress through as their understanding in relevant content areas increases. By appreciating these and by being ready with challenges to understanding at every stage, they would be more able to guide and stimulate their students' learning. In part, this may be achieved by exposure to relevant topics in the vast collection of information of this sort that is available in the literature. Again, however, learning to listen to children is likely the best way to achieve this understanding.

# VI. FUTURE DIRECTIONS

## 6.1. How Important is Reflection to the Development of Scientific Thinking?

### 6.1.1. Using a reflective context to develop domain-general metacognitive strategies.

Based on this study, it is evident that students in Grades Five and Six operate at two levels of scientific thought within at least three distinct frameworks. The first of these centers around the focus of inquiry (Section 4.3.1) that drives their investigations:

1. Level 2 FOI: Students' investigations focus on WWHI investigations aimed at testing external variables.
2. Level 3 FOI: Students' investigations focus on testing ideas. Explicit recognition of the need to identify observable implications may or may not occur at this point.

The second focuses on analogical reasoning skill (Section 4.3.2):

1. Level 2 AR: Students map analogies, but do not consistently evaluate the applicability of the analog relationships with which they are working.
2. Level 3 AR: Students map analogies and consistently evaluate the applicability of the analog relationships with which they are working.

The third focuses on the ability to develop implications-based investigations (Section 4.3.3):

1. Level 2 IE: Students attempt to explain a variety of phenomena with a proposed theory as a means of determining whether it may be applied consistently.
2. Level 3 IE: Students deliberately seek observable implications as a means of testing a proposed theory.

Several students displayed a generalized understanding of both Level 2 and Level 3 FOI that appears to be domain-general. Although Level 3 AR and IE were observed in certain contexts, generalized understanding of these levels was not observed. It remains unclear whether a reflective focus on the differences between Level 2 and Level 3 FOI / AR / IE could consistently drive progress from Level 2 to Level 3. It is possible that taking part in the idea-generation / debate process described here would generate similar outcomes without direct reflection on the strategies used in doing so. To more clearly identify the roles of participation and reflection, a comparison between students encouraged to reflect in this manner with those who are not is needed. Furthermore, it is possible that a teacher who is aware of the distinctions between the categories could effectively challenge students to progress from Level 2 to Level 3 without their ever having directly articulated the nature of the transition that they are experiencing. Based on these two concerns, validation of the structure presented here needs to include a comparison of the following groups:

1. a control group in which students are expected to develop, share, and test their ideas and in which those ideas are challenged by their peers
2. an experimental group in which the students are expected to develop, share and test their ideas and in which those ideas are challenged by a teacher familiar with the identified framework as well as by other students; direct reflection on the nature of the strategies used in doing so should not be encouraged in this group.
3. an experimental group in which the students are expected to develop, share, and test ideas and in which those ideas are challenged by a teacher familiar with the identified framework as well as by other students; direct reflection on

the nature of the strategies used in doing so should be encouraged in this group.

Ideally, the same teacher should work with all three groups, and certainly with both of the experimental groups. The study should be longitudinal so that changes in students' investigative frameworks over a period of two to three years (e.g. from Grade Four to Grade Six) could be investigated.

Informal observations of students with whom I have worked, and who I have been able to guide more effectively since completing this study, suggest that most students are able to articulate a clear understanding of Level 2 AR and that at least some are able to articulate a Level 3 understanding. Transcript analysis has revealed areas in which students came very close to articulating an understanding of Level 3 IE. It seems likely that with better guidance, students on the verge of this transition would have been able to develop the understandings that appear to be necessary to make this happen. A study such as the one described here would be useful in testing this idea more systematically.

### 6.1.2. Is it possible for students in Grade Five / Six to develop Level 4 FOI / AR / IE understandings?

If immersed in the type of classroom science described in this study for a longer period of time (i.e. two to three years), it is possible that students could progress to levels not observed in this study. If more guided reflection would make the significant difference hypothesized in Section 6.1.1, it seems likely that the students would then be ready to move to Level 4.

### 6.1.3. At what point do strategies become domain-general?

I have proposed that certain types of reasoning may be evident in familiar domains primarily because when content is clearly understood, the plausibility of analogs or the identification of implications becomes obvious. By reflecting on the higher levels of reasoning that may occur in these contexts, I have suggested that a more domain-general understanding may be achieved. Some evidence of this process has been gathered in this study, but further documentation is needed. The development of domain-general understandings likely requires the identification of the use of a particular strategy in a variety of contexts. It would be helpful to know how many familiar situations must be analyzed before such generalities become apparent and the rate of variation at which this process may take place for different students.

Most of the students who took part in this study were able to refute the applicability of transferring animist explanatory structure from a base to a target analog. It is unclear whether reflection on this context would facilitate a broader understanding of the nature of analogy that could be systematically applied in other domains. Again, informal observations suggest that for some students, this context may be a very productive base for achieving the desired domain-general understanding. Detailed observations of this process are needed to answer this question more fully. Similar observations could be made for all three of the broad categories as well as for those pertaining to controlled experimentation (Section 4.3.4.1), measurement devices and techniques (Section 4.3.4.2), and data analysis (Section 4.3.4.3).

In observing the development of these understandings, care should be taken to observe differential effects of reflection on strong and weak students (as measured by FOI / AR / IE frameworks). If advanced thinking strategies are already automatic in some students, conscious attention to them could encumber a previously fluid process. It seems plausible, however, that these effects could allow them to be dealt with in a rational manner. FOI understandings likely also need to be conscious understandings for them to be effective. This need not suggest conscious control over the entire creative process. Research indicates that an "incubation stage" during which ideas are not consciously processed is an important component of creativity (Armbruster, 1989, p. 179). When new ideas are recognized, however, they may then be evaluated in a conscious and systematic manner, resulting in the further development of knowledge structures that could then affect the development of more new ideas.

## 6.2. Validation of Empirical and Communicative Frameworks

### 6.2.1. Validation of the level-structure for empirical procedures.

More detailed documentation supporting the existence of the three categories pertaining to empirical procedures (Section 4.3.4) is needed. The levels described here could serve as an initial observational framework for an investigation of this nature.

### 6.2.2. Validation of the level-structure for communicative strategies.

More detailed documentation supporting the existence of the framework describing developmental levels of communicative strategies (Section 4.3.5) is needed. Again, the levels discussed here could serve as an initial observational framework for this investigation.

## 6.3. Further Development of Level 1 Frameworks

### 6.3.1. What is an optimum degree of focus?

As is discussed in Appendix H.3, the role that free exploration plays in the development of scientific understanding is unclear at this point. A detailed analysis of how work done with young children relates to that done here may shed some light on this issue. To understand fully the role of focus, careful analysis of the motivations behind young children's activity is needed. A related issue pertains to the potential role that WWHI activity may play in the development of understandings of new content among students at Level 3 FOI or beyond.

## 6.4. The Development of Integrated Knowledge Structures

### 6.4.1. Do spontaneous reduction strategies correlate with analogy-generation and / or evaluation?

In Section 4.3.2, I suggested that it is very difficult to will an analogy and that focusing on evaluation of those that naturally come to mind may constitute a more productive focus than trying to find ways to generate more or better analogs. However, if a tendency to reduce understandings to salient features in fact helps to promote the integration of knowledge structures (as is proposed in Appendix G.1), then this tendency should lead to both a qualitative and quantitative difference in generated analogies. If such a relationship is confirmed, it would be worthwhile to more clearly describe the process of reduction and to then determine whether the ability to reduce ideas is something that can be learned. In Appendix G.2, I propose mapping as a potential causal mechanism for the formation of reduced knowledge structures, suggesting that reductions are nothing more than the common elements of mapped analogical relationships whose reduction becomes apparent through recognition of shared structure. If this is the case, perhaps encouraging students to map more carefully the analogs that they already generate could lead to a greater tendency to reduce ideas. This could then help foster the development of more analog relationships and thereby stimulate a positive-feedback loop that could enhance the entire creative process.

### 6.4.2. Do students who frequently engage in Level 3 FOI demonstrate a quantitative or qualitative difference in the nature of the analogies that they generate?

It is plausible that the students who are most capable of identifying and validating analog relationships could also have an advantage in their ability to develop predictive implications, as these are often identified by analogy. In these cases, such ability may not involve the conscious identification of implications, because the students may simply identify more implications as they come unbidden to mind as analogies. Observing the relationship between the nature of analogies generated and the ability to formulate testable implications would help to clarify the nature of the interdependence of these categories. In Section 4.3.1, I suggest that the ability to engage in theory-based experimentation at Level 3 FOI could be an important contributor to the development of integrated knowledge structures. If so, a positive feedback loop much like that described in Section 6.4.1 may also be evident in the relationship between skill in analogical reasoning and Level 3 FOI.

### 6.4.3. How does the tendency to overgeneralize affect analogical reasoning skill?

Observations of students during this study suggest that although reduced knowledge may promote the identification of a wide variety of analog relationships, it may also lead to assumed equivalence of explanatory structure where it does not exist. If the mapping of identified analog relations is able to foster integrated knowledge structures in the manner suggested in Section 6.4.1, then it is quite plausible that students could generate a wide variety of analogs and still be classified at Level 2 AR (as was shown in Section 4.3.2.2.3). However, this raises a question regarding why these students are more likely to map perceived likeness in the first place. A one- to two-year case study of a small number of students with observed tendencies to reason in this manner could shed further light on the causes and implications of this type of thinking.

## 6.5. Developing Productive Contexts for Investigation

### 6.5.1. Productive contexts for student investigation.

Both the electricity and the chemistry units that provided the context for this study began with broad general questions that allowed the development of specific content and procedural knowledge, and, at the same time, allowed the students the freedom to develop and test their own theories. Developing lists of other contexts which are as or more conducive to the development of concepts deemed important as qualitative bases for more advanced understandings would be helpful in developing open-ended curricula that address important understandings that students will later be expected to acquire. Certain events or questions would be more likely than others to (a) capture students' attention, (b) prompt questions that lead to interesting investigations that are possible within the confines of an elementary classroom, and (c) promote the development of basic scientific understandings. Identification of questions such as these needs to become an active area of research.

Similarly, compiling diverse arguments effective in challenging commonly held views would allow teachers greater flexibility in their approaches to facilitating knowledge construction in their classrooms. These, too, need to be investigated through further research.

### 6.5.2. Developing a repertoire of carefully evaluated analogs.

It appears that certain phenomena may recur frequently as potential source analogs (e.g. fire, water, the nature of life). If this is the case, identifying these and using them as topics for investigation could greatly help student reasoning. If these were more clearly understood, their explanatory structure could be more rationally applied in relevant cases and could be avoided in cases where the analogical relationship is not valid. Identifying a list of phenomena such as these would be very useful in developing curricula that take these ideas into account.

### 6.5.3. Generalizability to larger class sizes.

Although the methods of constructing meaning used by the individual students who took part in this study were likely independent of the class size in which their thinking took place, the effectiveness of specific classroom techniques for eliciting those types of thinking would almost certainly be heavily influenced by this factor. Further research is necessary to determine how student thinking could best be facilitated in a larger, more realistic classroom setting.

## 6.6. Technological Frameworks

### 6.6.1. How would a technological framework differ from the theoretical framework identified in this study?

The identification of a developmental framework pertaining to the manner in which students approach technical problem-solving tasks would allow useful comparisons between technically and theoretically motivated activity. Although some overlap seems inevitable, it is possible that there are some ways of thinking that would be helpful in one context and a hindrance in the other. Clarifying the manner in which children approach both types of activity would make possible the identification of more specific objectives describing desired thinking skills and habits. It may be useful for students to learn to identify the type of focus that they need to use so that they do not spend too much time figuring out theoretical explanations when a practical outcome is all that is desired or so that they do not contort theoretical questions to fit their own pragmatic agendas.

### 6.6.2. What role does theoretical motivation play in determining the level at which students approach inquiry (FOI)?

It appears that some students are more inclined, be it motivationally, intellectually, or both, toward either theoretical or practical tasks. If this is the case, it may be helpful to allow students to focus on their area of strength while helping them to develop understanding and skill in the other in a manner that complements their primary interest area. Further research designed to identify the characteristic strengths and weaknesses of students in these categories would be helpful in meeting the needs of both groups.

## REFERENCES

Abrams, E., & Wandersee, J. (1995). How does biological knowledge grow? A study of life scientists' research practice. *Journal of Research in Science Teaching, 32*, 649-663.

Alberta Education (1983). *Elementary Science: Curriculum guide.* Edmonton, Canada: Curriculum Branch.

Alberta Education (1987). *Students' thinking: Developmental framework cognitive domain.* Edmonton, Canada.

Alberta Education (1996). Science. *Program of studies: Elementary schools.* Edmonton, Canada: Curriculum Standards Branch.

Alberti, D., Davitt, R., Ferguson, T., & Repass, S. (1974). *Teacher's guide for gases and "airs": Nature of air and behavior of gases.* Toronto: McGraw-Hill.

Arends, C. (1995). Reaching. On *I can hear you* [compact disk]. Nashville, TN: Edward Grant / running arends music.

Armbruster, B. (1989). Metacognition in creativity. In J. Glover, R. Ronning, & C. Reynolds (Eds.), *Handbook of creativity* (pp. 177-182). New York: Plenum Press.

Baird, J., Fensham, P., Gunstone, R., & White, R. (1991). The importance of reflection in improving science teaching and learning. *Journal of Research in Science Teaching 28*, 163-182.

Barell, J. (1995). *Teaching for thoughtfulness.* New York: Longman.

Bogdan, R., & Biklen, S. (1992). *Qualitative research for education: An introduction to theory and methods (2nd ed.).* Needham Heights, MA: Allyn and Bacon.

Bronowski, J. (1964). *Science and human values.* London: Penguin Books.

Brown, D. (1992). Using examples and analogies to remediate misconceptions in physics: Factors influencing conceptual change. *Journal of Research in Science Teaching, 29*, 17-34.

Brown, D. (1993). Refocusing core intuitions: A concretizing role for analogy in conceptual change. *Journal of Research in Science Teaching, 30*, 1273-1290.

Brown, D., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. *Instructional Science, 18*, 237-261.

Caravita, S., & Halldén, O. (1994). Re-framing the problem of conceptual change. *Learning and Instruction, 4*, 89-111.

Carey, S. (1985). Are children fundamentally different kinds of thinkers and learners than adults? In S. Chipman, J. Segal, & R. Glaser (Eds.), *Thinking and learning skills: Volume 2: Research and open questions* (pp. 485-517). Hillsdale, NJ: Lawrence Erlbaum.

Carey, S. (1995). On the origin of causal understanding. In D. Sperber (Ed.), *Causal cognition: A multidisciplinary debate* (pp. 268-308). New York: Oxford University Press.

Carey, S. (1996). Cognitive domains as modes of thought. In D. Olson & N. Torrance (Eds.), *Modes of thought: Explorations in culture and cognition* (pp. 187-215). New York: Cambridge University Press.

Carey, S., Evans, R., Honda, M., Jay, E., & Unger, C. (1989). "An experiment is when you try it and see if it works": A study of grade 7 students' understanding of the construction of scientific knowledge. *International Journal of Science Education, 11*, 514-529.

Carey, S., & Smith, C. (1995). On understanding the nature of scientific knowledge. In D. Perkins, J. Schwartz, M. West, & M. Wiske (Eds.), *Software goes to school: Teaching for understanding with new technologies* (pp. 39-55). New York: Oxford University Press.

Carey, S., & Spelke, E. (1994). Domain-specific knowledge and conceptual change. In L. Hirschfeld & S. Gelman (Eds.), *Mapping the mind: Domain specificity in cognition and culture* (pp. 169-200). New York: Cambridge University Press.

Carr, M., Barker, M., Bell, B., Biddulph, F., Jones, A., Kirkwood, V., Pearson, J., & Symington, D. (1994). The constructivist paradigm and some implications for science content and pedagogy. In P. Fensham, R. Gunstone, & R. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 147-160). Bristol, PA: The Falmer Press.

Champagne, A., Gunstone, R., & Klopfer, L. (1985). Instructional consequences of students' knowledge about physical phenomena. In L. West and A. Pines (Eds.), *Cognitive structure and conceptual change* (pp. 61-90). Orlando, FL: Academic Press.

Clement, J. (1981). Analogy generation in scientific problem solving. *Proceedings of the Third Annual Conference of the Cognitive Science Society*, 137-140.

Clement, J. (1982). Analogical reasoning patterns in expert problem solving. *Proceedings of the Fourth Annual Conference of the Cognitive Science Society*, 79-81.

Clement, J. (1986). Methods for evaluating the validity of hypothesized analogies. *Eighth Annual Conference of the Cognitive Science Society*, 223-234.

Clement, J. (1988). Methods for generating analogies. *Cognitive Science, 12*, 563-586.

Clement, J. (1989a). Generation of spontaneous analogies by students solving science problems. In D. Topping, D. Crowell, & V. Kobayashi (Eds.), *Thinking across cultures: The Third International Conference on Thinking* (pp. 303-308). Hillsdale, NJ: Lawrence Erlbaum.

Clement, J. (1989b). Learning via model construction and criticism: Protocol evidence on sources of creativity in science. In J. Glover, R. Ronning, & C. Reynolds (Eds.), *Handbook of creativity* (pp. 341-381). New York: Plenum Press.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in Physics. *Journal of Research in Science Teaching, 30*, 1241-1257.

Clement, J. (1994). Use of physical intuition and imagistic simulation in expert problem solving. In D. Tirosh (Ed.), *Implicit and explicit knowledge: An educational approach* (pp. 205-244). Norwood, NJ: Ablex.

Clement, J. (in press). Expert novice similarities and instruction using analogies. To appear in *International Journal of Science Education.*

Clement, J., Brown, D., & Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding "anchoring conceptions" for grounding instruction on students' intuitions. *International Journal of Science Education, 11*, 554-565.

Cosgrove, M. (1995). A study of science-in-the-making as students generate an analogy for electricity. *International Journal of Science Education, 17*, 295-310.

Council of Ministers of Education, Canada. (1996). Foundation statements for K-12 Science. *Consultative draft of the common framework of science learning outcomes K to 12: Pan-Canadian Protocol for collaboration on school curriculum.*

Dagher, Z. (1995). Review of studies on the effectiveness of instructional analogies in science education. *Science Education, 79*, 295-312.

di Sessa, A. (1983). Phenomenology and the evolution of intuition. In D. Gentner and A. Stevens (Eds.), *Mental models* (pp. 15-33). Hillsdale, NJ: Lawrence Erlbaum.

di Sessa, A. (1988). Knowledge in pieces. In G. Forman (Ed.), *Constructivism in the computer age* (pp. 49-70). Hillsdale, NJ: Lawrence Erlbaum.

Doig, B., Groves, S., & Clark, J. (1995, December). Stimulated recall interviews: A cautionary tale. Paper presented at the symposium Contemporary Approaches to Research in Mathematics, Science, Health and Environmental Education, Deakin University, Melbourne, Australia.

Driver, R. (1989). Students' conceptions and the learning of science. *International Journal of Science Education, 11*, 481-490.

Driver, R., Asoko, H., Leach, J., Mortimer, E., & Scott, P. (1994). Constructing scientific knowledge in the classroom. *Educational Researcher 23* (7), 5-12.

Duckworth, E. (1990). Opening the world. In E. Duckworth, J. Easley, D. Hawkins, A. Henriques, & D. Trumbull, *Science education: A minds-on approach for the elementary years* (pp. 21-59). Hillsdale, NJ: Erlbaum.

Duckworth, E. (1996). *"The having of wonderful ideas" and other essays on teaching and learning (2nd Ed.).* New York: Teachers College Press.

Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science Education, 75*, 649-672.

Duschl, R., Hamilton, R., & Grandy, R. (1992). Psychology and epistemology: Match or mismatch when applied to science education? In R. Duschl & R. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice* (pp. 19-47). Albany, NY: State University of New York Press.

Dykstra, Dewey, Jr. (1996). Teaching introductory physics to college students. *Constructivism: Theory, perspectives, and practice* (pp. 182-204). New York: Teachers College Press.

Ellis, J. (1998). *Teaching from understanding: Teacher as interpretive inquirer.* New York: Garland.

Fensham, P., Gunstone, R., & White, R. (1994). Introduction. In P. Fensham, R. Gunstone, & R. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 1-13). Bristol, PA: The Falmer Press.

Feynman, R. (1985). *"Surely you're joking, Mr. Feynman."* Adventures of a curious character. New York: W. W. Norton and Company.

Feynman, R. (1988). *"What do you care what other people think?" Further adventures of a curious character.* Toronto: Bantam Books.

Feynman, R. (1995). *Six easy pieces: Essentials of physics explained by its most brilliant teacher.* Don Mills, Canada: Addison-Wesley.

Fosnot, C. (1989). Enquiring teachers, enquiring learners: A constructivist approach for teaching. New York: Teachers College Press.

Fosnot, C. (1996). Teachers construct constructivism: The center for constructivist teaching / teacher preparation project. *Constructivism: Theory, perspectives, and practice* (pp. 205-216). New York: Teachers College Press.

Friedl, A. (1972). *Teaching science to children: The inquiry approach applied.* New York: Random House.

Gardner, H. (1982). *Art, mind, and brain: A cognitive approach to creativity.* New York: Basic Books.

Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences.* New York: Basic Books.

Gardner, H. (1991). *The unschooled mind.* New York: Basic Books.

Gentner, D. (1981). Generative analogies as mental models. *The Third Annual Conference of the Cognitive Science Society*, 97-100.

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science, 7*, 155-170.

Gentner, D., & Gentner D. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner and A. Stevens (Eds.), *Mental models* (pp. 99-310). Hillsdale, NJ: Lawrence Erlbaum.

Gilbert, J., & Swift, D. (1985). Towards a Lakatosian analysis of the Piagetian and alternative conceptions research programs. *Science Education, 69*, 681-696.

Glynn, S. (1991). Explaining science concepts: A teaching-with-analogies model. In S. Glynn, R. Yeany, & B. Britton (Eds.), *The psychology of learning science* (pp. 219-240). Hillsdale, NJ: Lawrence Erlbaum.

Glynn, S. (1994). Teaching science with analogy: A strategy for teachers and textbook authors. University of Georgia. (National Reading Research Center, Reading Research Report No. 15).

Gould, S. (1996). *Full house: The spread of excellence from Plato to Darwin.* New York: Three Rivers Press.

Grosslight, L., Unger, C., Jay, E., & Smith, C. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*, 799-822.

Gunstone, R. (1994). The importance of specific science content in the enhancement of metacognition. In P. Fensham, R. Gunstone, & R. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 131-146). Bristol, PA: The Falmer Press.

Gunstone, R., & Northfield, J. (1994). Metacognition and learning to teach. *International Journal of Science Education, 16*, 523-537.

Hardwicke, A. J. (1995). Using molecular models to teach chemistry. Part 1: Modelling molecules. *School Science Review, 77*, 59-64.

Harrison, A., & Treagust, D. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education, 80*, 509-534.

Hawkins, D. (1990). Defining and bridging the gap. In E. Duckworth, J. Easley, D. Hawkins, A. Henriques, & D. Trumbull, *Science education: A minds-on approach for the elementary years* (pp. 97-139). Hillsdale, NJ: Erlbaum.

Henriques, A. (1990). Experiments in teaching. In E. Duckworth, J. Easley, D. Hawkins, A. Henriques, & D. Trumbull, *Science education: A minds-on approach for the elementary years* (pp. 141-186). Hillsdale, NJ: Erlbaum.

Hodson, D. (1996). Laboratory work as scientific method: Three decades of confusion and distortion. *Journal of Curriculum Studies, 28* (2), 115-135.

Jenkins, E. (1996). The 'nature of science as a curriculum component." *Journal of Curriculum Studies, 28*, 137-150.

Julyan, C. & Duckworth, E. (1996). A constructivist perspective on teaching and learning science. *Constructivism: Theory, perspectives, and practice* (pp. 55-72). New York: Teachers College Press.

Karmiloff-Smith, A., and Inhelder, B. (1975). "If you want to get ahead, get a theory." *Cognition 3*, 195-212.

Kass, H. (1992). Teaching for conceptual change. *Senior high science teacher resource manual.* Edmonton, Canada: Alberta Education.

Kitchener, K, & King, P. (1981). Reflective judgment: Concepts of justification and their relationship to age and education. *Journal of Applied Developmental Psychology, 2*, 89-116.

Kitchener, R. (1992). Piaget's genetic epistemology: Epistemological implications for science education. In R. Duschl & R. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice* (pp. 116-146). Albany, NY: State University of New York Press.

Klaassen, C., & Lijnse, P. (1996). Interpreting students' and teachers' discourse in science classes: An underestimated problem? *Journal of Research in Science Teaching 33*, 115-134.

Kuhn, D. (1996). Is good thinking scientific thinking? In D. Olson & N. Torrance (Eds.), *Modes of thought: Explorations in culture and cognition* (pp. 261-281). New York: Cambridge University Press.

Kuhn, T. (1970). *The structure of scientific revolutions.* Chicago: The University of Chicago Press.

Lawson, A. (1993). The importance of analogy: A prelude to the special issue. *Journal of Research in Science Teaching, 30,* 1213-1214.

Liem, T. (1987). *Invitations to Science Inquiry (2nd Ed.).* Chino Hills, CA: Science Inquiry Enterprises.

Linn, M., & Burbules, N. (1993). Construction of knowledge and group learning. In K. Tobin (Ed.), *Constructivism in science education.* Hillsdale, NJ: Lawrence Erlbaum.

Marton, F., Fensham, P., & Chaiklin, S. (1994). A Nobel's eye view of scientific intuition: Discussions with the Nobel prize-winners in physics, chemistry and medicine (1970-86). *International Journal of Science Education, 16,* 457-473.

Mason, L. (1994). Cognitive and metacognitive aspects in conceptual change by analogy. *Instructional Science, 22,* 157-187.

Melnychuk, R., Jacknicke, K., & Visscher, H. (1970). *Nuffield Biology.* Ontario, Canada: Longmans Canada.

Merriam, S. (1988). *Case study research in education.* London: Jossey-Bass Publishers.

Millar, R. (1989). Constructive criticisms. *International Journal of Science Education, 11,* 587-596.

Millar, R., & Driver, R. (1987). Beyond processes. *Studies in Science Education, 14,* 63-82.

Millar, R., & King, T. (1993). Students' understanding of voltage in simple series electric circuits. *International Journal of Science Education, 15,* 339-349.

Millar, R., Lim Beh, K., & Alam, S. (1993). Students' understanding of voltage in simple parallel electric circuits. *International Journal of Science Education, 15,* 351-361.

Mishler, E. (1986). The analysis of interview-narratives. In T. Sarbin (Ed.), *Narrative psychology: The storied nature of human context* (pp. 233-255). New York: Praeger.

Monastersky, R. (1998). The rise of life on Earth. *National Geographic, 193* (3), 54-81.

Moshman, D. & Lukin, L. (1989). The creative construction of rationality. In J. Glover, R. Ronning, & C. Reynolds (Eds.), *Handbook of creativity* (pp. 183-198). New York: Plenum Press.

Munby, H. (1982). *What is scientific thinking?* Ottawa, Canada: Minister of Supply and Services.

Nadeau, R. & Désautels, J. (1984). *Epistemology and the teaching of science.* Ottawa, Canada: Guidance Center, University of Toronto.

Norris, S. (1992). Practical reasoning in the construction of scientific knowledge. In R. Duschl & R. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice* (pp. 195-225). Albany, NY: State University of New York Press.

Nersessian, N. (1992a). How do scientists think? Capturing the dynamics of conceptual change in science. In R. Giere (Ed.), *Cognitive models of science* (pp. 3-44). Minneapolis, MN: The University of Minnesota Press.

Nersessian, N. (1992b). Constructing and instructing: The role of "abstraction techniques" in creating and learning Physics. In R. Duschl & R. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice* (pp. 48-68). Albany, NY: State University of New York Press.

Osborne, J. (1996). Beyond constructivism. *Science Education, 80*, 53-82.

Osborne, R. (1983). Towards modifying children's ideas about electric current. *Research in Science and Technological Education, 1*, 73-82.

Piaget, J. (1967). *The child's conception of the world.* London: Routledge and Kegan Paul.

Posner, G., Strike, K., Hewson, P., & Gertzog, W. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*, 211-227.

Pressley, M., & Woloshyn, V (1995). *Cognitive strategy instruction that really improves children's academic performance* (pp. 213-233). Cambridge, MA: Brookline Books.

Roberts, D. (1983). *Scientific literacy: Towards balance in setting goals for school science programs.* Ottawa, Canada: Minister of Supply and Services.

Roberts, R. (1989). *Serendipity: Accidental discoveries in science.* Toronto, Canada: Frank Wiley & Sons.

Sagan, C. (1977). *The dragons of Eden.* Ballantine Books: New York.

Sagan, C. (1993). *Pale blue dot.* Random House: New York.

Sagan, C. (1996). *The demon-haunted world.* Random House: New York.

Saxena, A. (1992). An attempt to remove misconceptions related to electricity. *International Journal of Science Education, 14,* 157-162.

Schifter, D. (1996). On teaching and learning mathematics. In C. Fosnot (Ed.), *Constructivism: Theory, perspectives, and practice* (pp. 73-91). New York: Teachers College Press.

Schultz, K., & Clement, J. (1994). "The use of class discussion and analogies in teaching: Examples from one physics classroom." In C. Camp & J. Clement, *Preconceptions in mechanics: Lessons dealing with students' conceptual difficulties.* Dubuque, IA: Kendall-Hunt.

Segal, G., & Cosgrove, M. (1995). *Promoting loud thinking about light in elementary school science.* Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, San Francisco, CA.

Shepardson, D. & Moje, E. (1994). The nature of fourth graders' understandings of electric circuits. *Science Education, 75,* 459-514.

Shipstone, D. (1984). A study of children's understanding of electricity in simple DC circuits. *European Journal of Science Education, 6,* 185-198.

Smith, D., & Neale, C. (1989). The construction of subject matter knowledge in primary science teaching. *Teaching & Teacher Education, 5* (1), pp. 1-20.

Spiro, R, Feltovich, P., Coulson, R., & Anderson, D. (1989). Multiple analogies for complex concepts: Antidotes for analogy-induced misconception in advanced knowledge acquisition. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 498-531). New York: Cambridge University Press.

Strike, K., & Posner, G. (1992). A revisionist theory of conceptual change. In R. A. Duschl and R. J. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice* (p. 147-176). Albany, NY: State University of New York Press.

Sutton, C. (1993). Figuring out a scientific understanding. *Journal of Research in Science Teaching, 30,* 1215-1227.

Summers, M. (1992). Improving primary school teachers' understanding of science concepts – Theory into practice. *International Journal of Science Education, 14,* 25-40.

Sylwester, R. (1995). *A celebration of neurons.* Alexandria, VA: Association for Supervision and Curriculum Development.

Treagust, D., Duit, R., & Fraser, B. (1996). Overview: Research on students' preinstructional conceptions - The driving force for improving teaching and learning in science and mathematics. In D. Treagust, R. Duit, & B. Fraser (Eds.), *Improving teaching and learning in science and mathematics* (pp. 1-14). New York: Teachers College Press.

Trumbull, D. (1990). Introduction. In E. Duckworth, J. Easley, D. Hawkins, A. Henriques, & D. Trumbull, *Science education: A minds-on approach for the elementary years* (pp. 1-20). Hillsdale, NJ: Erlbaum.

Tweney, R. (1991). Informal reasoning in science. In J. F. Voss, D. N. Perkins, & J. W. Segal (Eds.), *Informal reasoning and education* (pp. 3-16). Hillsdale, NJ: Erlbaum.

von Glaserfeld, E. (1993). Questions and answers about radical constructivism. In K. Tobin (Ed.), *The practice of constructivism in science education* (pp. 23-38). Hillsdale, NJ: Erlbaum.

Vosniadou, S. (1987). Children and metaphors. *Child Development, 58*, 870-885.

Vosniadou, S. (1989). Analogical reasoning as a mechanism in knowledge acquisition: A developmental perspective. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 413-437). New York: Cambridge University Press.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*, 45-69.

Vosniadou, S., & Brewer, W. (1987). Theories of knowledge restructuring in development. *Review of Educational Research, 57* (1), 51-67.

Vosniadou, S., & Brewer, W. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*, 535-585.

Wallace, J. & Louden, W. (1992). Science teaching and teachers' knowledge: Prospects for reform of elementary classrooms. *Science Education, 76*, 507-521.

Watts, M. (1994). Constructivism, re-constructivism and task-orientated problem-solving. In P. Fensham, R. Gunstone, & R. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 39-58). Bristol, PA: The Falmer Press.

Weber, S. J. (1986). The nature of interviewing. *Phenomenology and Pedagogy, 45* (2), 65-72.

White, R. (1994). Dimensions of content. In P. Fensham, R. Gunstone, and R. White (Eds.), *The content of science: A constructivist approach to its teaching and learning* (pp. 255-262). Bristol, PA: The Falmer Press.

Whitehead, A. N. (1929). *The aims of education.* New York: Macmillan.

Wittrock, M. C. (1994). Generative science teaching. *The content of science: A constructivist approach to its teaching and learning* (pp. 29-38). Bristol, PA: The Falmer Press.

Wong, E. (1993a). Self-generated analogies as a tool for constructing and evaluating explanations of scientific phenomena. *Journal of Research in Science Teaching, 30,* 367-380.

Wong, E. (1993b). Understanding the generative capacity of analogies as a tool for explanation. *Journal of Research in Science Teaching, 30,* 1259-1272.

Wong, E. (1996). Students' scientific explanations and the contexts in which they occur. *The Elementary School Journal, 96,* 295-509.

# APPENDIX A

## Sample Third-Level Responses for "awareness of the use of the analogy in changing initial mental models" (Mason, 1994, p. 177)

### A.1. Sample Third-Level Responses for "awareness of the use of the analogy in changing initial mental models" (Mason, 1994, p. 177)

The following student responses are taken from Mason (1994, pp. 177-178).

1. Yes, I changed many beliefs. Before I believed that the blood does not flow into vessels, but freely into the body. Moreover I thought that blood leaves from the brain, but now I know that the heart contains both the oxygenated blood (left side) and the blood with carbon dioxide (right side) until it pushes both to the lungs.

2. I knew that the blood leaves from the heart, but I did not know that it goes to the lungs, that it follows two paths. I thought that the blood had to return to the lungs, that it follows two paths. I thought that the blood had to return to the heart, but my belief was that dirty blood is cleaned by the heart with some acids.

3. I believe that the heart cleaned the dirty blood as I did not know the function of the lungs and the relationship between the lungs and the heart. I believed that because I had seen pictures where the clean, red blood is in the left side of the heart, and the dirty, blue blood is in the right side of the heart, so I was forced to believe that the blood was cleaned in the middle of the heart by the heart itself. Now, I know that the blood goes to the lungs to pick oxygen up and to lose carbon dioxide and that the heart pumps the two types of blood.

4. The postman's two routes made it easy to understand the two types of blood and the two circulations in our body. At the beginning I wrote that the heart is necessary to breathe because when I am out of breath, after running, for example, I feel my heart beats faster and faster, so I believed that it was the heart that makes it possible to breathe but now I believe that the heart just pumps blood. [Although this student claims that "the postman's two routes made it easy to understand the two types of blood," she does not explain how the analogy affected her understanding.]

5. I have changed my belief. Before I could not understand the two colors, the red one and the blue one used in the pictures of the inside of our body showing the heart, because I did not know that the blood becomes oxygen-poor so it has to go to the lungs to be filled with oxygen. [It seems unlikely that the resolution of the blue-blood issue was due to the postal analogy].

6. I now the postman, he comes every morning. By thinking of the postman I understand how the blood travels. When I do not remember something, I can remember what the postman does...I just knew that there were the heart and the veins. When I was very young I thought that if I cut the skin where there was a vein, blood flowed, flowed and then I would die. Now, I know that there are platelets inside the blood. [It is unclear whether the postal analogy helped her to develop this understanding or if it is merely a means of remembering how the circulatory system functions.]

# APPENDIX B

## Consent Letters

1. Letter of consent (classroom observation only).
2. Letter of consent (individual interviews).

## B.1. Letter of consent (classroom observation).

Dear Parents of Grade Five and Six Students:

I am conducting a study of the manner in which students in Grades Five and Six generate and evaluate ideas in science. I am writing this letter to request permission for your child to participate in the study.

The research will be based upon regular classroom activities that take place from December 1997 to June 1998. It will involve the students sharing their ideas, generating arguments for and against their own and others' ideas, and developing criteria to evaluate the quality of their arguments. Throughout such activities and discussions, the students will be asked to share the sources of their ideas and arguments. This will help both the students and me to gain a better understanding of how they think. These are activities that would normally take place as part of science class in order to help students develop an understanding of science concepts and methods.

If you agree to allow your child to participate, I would use the information that I gather to help me better understand how children generate and evaluate questions, ideas, and arguments. By analyzing the information, I hope to gain a better understanding of what factors help students to be proficient in these areas so that I may more effectively help them to further develop these skills in ways that are meaningful to them. I may use specific examples of student ideas and / or work to support the ideas that I will be developing, but will not release any information that would lead to the identification of the students being represented. In order to respect the privacy of participants, all names, locations, and identifying information will be excluded from the presentation of my results.

If you would be willing to allow me to analyze the comments that your child contributes to science discussions and the manner in which he or she takes part in class activities, please sign the attached permission form and return it to the school. If you have any questions, please feel free to call me at school (725-3755) or at home (362-5575). If you wish, you may also contact my supervisor (Dr. Rick Mrazek) at the University of Lethbridge (329-2452) or any member of the Faculty of Education Human Subject Research Committee to obtain additional information. The chairperson of the research committee is Dr. Craig Loewen (329-2455). You may change your mind about having your child participate at any time during the study.

Thank you for your consideration of this matter,

Martina Freeman

****************************************************************************

I agree to allow my child, ______________________________, to participate in the study described in the above letter.

______________________________
Signature

______________________________
Date

### B.2. Letter of consent (individual interviews).

Dear Parents of Grade Five and Six Students:

I am conducting a study of the manner in which students in Grades Five and Six generate and evaluate ideas in science. I am writing this letter to request permission for your child to participate in the study.

The research will be based upon regular classroom activities that take place from December 1997 to June 1998. It will involve the students sharing their ideas, generating arguments for and against their own and others' ideas, and developing criteria to evaluate the quality of their arguments. Throughout such activities and discussions, the students will be asked to share the sources of their ideas and arguments. This will help both the students and me to gain a better understanding of how they think. These are activities that would normally take place as part of science class in order to help students develop an understanding of science concepts and methods.

In addition, I would like to interview three students outside of regular school time in order to gain a deeper insight into the nature of their ideas than I would be able to in a large-group setting. This will include an initial after-school interview that will deal with the general nature of their interests and how these relate to the manner in which they think scientifically. It will also involve approximately three more interviews that will focus more specifically on the ideas they share during class discussion and their thoughts as they participate in other classroom activities. I anticipate holding these interviews approximately once every two months.

If you agree to allow your child to participate, I would use the information that I gather to help me better understand how children generate and evaluate questions, ideas, and arguments. By analyzing the information, I hope to gain a better understanding of what factors help students to be proficient in these areas so that I may more effectively help them to further develop these skills in ways that are meaningful to them. I may use specific examples of student ideas and / or work to support the ideas that I will be developing, but will not release any information that would lead to the identification of the students being represented. In order to respect the privacy of participants, all names, locations, and identifying information will be excluded from the presentation of my results.

If you would be willing to allow your child to take part in the after-school interviews described above and willing to allow me to analyze the manner in which he or she participates in class activities, please sign the attached form and return it to the school. If you have any questions, please feel free to call me at school (725-3755) or at home (362-5575). If you wish, you may also contact my supervisor (Dr. Rick Mrazek) at the University of Lethbridge (329-2452) or any member of the Faculty of Education Human Subject Research Committee to obtain additional information. The chairperson of the research committee is Dr. Craig Loewen (329-2455). You may change your mind about having your child participate at any time during the study.

Thank you for your consideration of this matter,

Martina Freeman

**************************************************************************

I agree to allow my child, ______________________________, to participate in the study described in the attached letter.

______________________________
Signature

______________________________
Date

# APPENDIX C

## Interview Schedules

1. Initial narrative interview.
2. Think-aloud / reflective interview.
3. Classroom observation.

### C.1. Initial narrative interview.

- What was the best idea that you've ever had? How did you get it?
- What is something that you've always wondered about? Why does it puzzle you?
- What was the hardest thing you've ever figured out? How did you do it?
- If you could change one thing about the world, what would you change? Why?
- How do you feel about arguing with other people? Why?
- What do you know the most about? How are you able to remember so much?

### C.2. Think-aloud / reflective interview.

- What made you wonder about . . . . ?
- What made you think of . . . ?
- Which theory(ies) do you think make the most sense? Why?
- What do you consider to be your best / worst arguments? Why?
- Do you have a different idea that hasn't been suggested yet?
- Which theories are you certain are false? Why?
- What are you trying to find out?
- How do your results relate to your initial ideas?

### C.3. Classroom observation.

- Why do you ask?
- What made you think of that?
- Do you have any other ideas?
- What do you think of ___'s idea? Why?
- Which theory(ies) do you think make the most sense? Why?
- What are you trying to find out?
- How do your results relate to your initial ideas?

# APPENDIX D

## Progression of Activities in the Electricity Unit

1. Timeline.
2. Student-developed circuit diagrams.
3. "Thinking about Thinking" handout.
4. Summary of battery arguments.

## D.1. Timeline.

| Electricity Timeline | |
|---|---|
| Jan. 6 | - kids generated and discussed various circuit ideas (Appendix D.2) in response to question regarding how you could you light two or more bulbs with the same battery (introduced in relation to the idea of having a burglar alarm set off lights in more than one room of a model house at a time)<br>- discussed ways of testing different circuit-arrangements: How long would batteries in each last? How many bulbs would they light? How bright would the bulbs in each circuit be?<br>- introduced wire-jump diagrams to clarify which wires were touching in students' circuit diagrams<br>- discussed whether bulbs have positive and negative sides<br>- discussed if / when the direction of the battery matters<br>- decided to investigate the following questions:<br>  - How many lights can you light with one battery? (Jennifer)<br>  - How will the number of bulbs affect how the long the battery will last? (Robert)<br>  - How does the number of bulbs attached to one battery affect the brightness of the bulb? (Robert)<br>- discussed importance of battery direction in some situations, irrelevance in others (sparked by Rachel's question regarding whether bulbs have a positive and a negative side) |
| Jan. 7 | - used Frank's Capsella™ fan and switch to test the effect of battery reversal<br>- tested the effect of battery reversal on a flashlight; generated reasons for non-reversibility of batteries in some situations<br>- students started testing their circuits<br>- distributed circuit-diagram handout |
| Jan. 9 | - introduced and discussed "Thinking about Thinking" handout (Appendix D.3)<br>- shared and discussed results of circuit-testing from previous day<br>- discussed methods of untangling circuit diagrams to reduce confusion stemming from different interpretations of the drawings |
| Jan. 12 | - discussed reasons why a metal battery doesn't short-circuit itself (whole-group then small-group discussion regarding how batteries work) |

| | |
|---|---|
| Jan. 14 | - students identified important elements to look for when they took apart batteries:<br>  - acid type and location (Andrea)<br>  - connectors at each end (Carl)<br>  - ratio of black material to other substances in different-aged batteries (Frank, Andrea)<br>  - should use a voltmeter to determine age of batteries (Carl)<br>- dissected batteries |
| Jan. 19 | - written test on circuits; students were asked to:<br>  - explain the operation of a bulb and bulb holder<br>  - predict the relative brightness of bulbs in various series and parallel circuits<br>  - untangle circuit diagrams<br>  - develop a battery model<br>  - interpreting diagrams showing the operation of various electrical devices |
| Jan. 21 | - circuit test (continued)<br>(Jordan absent) |
| Jan. 23 | - discussed questions stemming from test: short circuits, logistics of various electrical devices, effect of connecting wire directly to bulb vs. connecting to bulb holder<br>- discussed observations necessary to answer questions identified January 6<br>- groups designed spreadsheets to monitor observations of original questions<br>(Carl absent) |
| Jan. 26 | - completed spreadsheets<br>- Robert, Carl, and Matthew started evaluating each other's battery explanations (from the test) by providing written comments and questions on photocopies of their diagrams / explanations |

| | |
|---|---|
| Jan. 28 | - discussed construction of light meters based on thickness of paper that a bulb can shine through<br>- achieved group consensus regarding how numerical values would be assigned (brightness = the greatest number of layers that the bulb can still be seen through; some groups assigned ranges of numbers to bright / dim categories)<br>- whole class worked on evaluating each other's battery models (written dialogues on photocopies of each other's diagrams / explanations; students were highly motivated to continue with this activity next day) |
| Jan. 30 | - continued written discussions of battery models<br>- individual interviews with Keith, Frank (regarding battery models) |
| Jan. 30 | - Keith's first battery interview |
| Feb. 2 | - continued written discussions of battery models<br>- individual interviews with Jennifer, Andrea (regarding battery models)<br>(Rachel absent) |
| Feb. 6 | - intended to set up tests to answer question identified on Day 1 and for which students had designed spreadsheets to monitor their observations, but discussion of what type of circuit that should be used; i.e. Samantha, Carl (Rebecca-B), or Rebecca C-style ( see Appendix D.2); Frank A, B, C, D, E consumed a large portion of the class<br>- discussed battery function; this stemmed from consideration of the implications of using different circuit arrangements (various arguments pertaining to one-way vs. two-way current; what happens to used energy, the nature of what is flowing, one-chambered vs. two-chambered battery)<br>(Carl absent) |
| Feb. 10 | - students read observation notes from previous class<br>- photocopied each group's spreadsheets to allow them to test Samantha, Carl, and Rebecca-style circuits separately<br>- some groups finished constructing light meters<br>- gathered equipment and began testing<br>(Frank absent) |

| | |
|---|---|
| Feb. 10, 11, 13; | - continued testing circuits |
| Feb. 16-20 | - no school |
| Feb. 23-27 | - no science classes (theater group at the school) |
| Mar. 2-4 | - continued testing circuits<br>(Robert absent Mar. 2-3; Andrea absent Mar. 2-4; Keith absent Mar. 4) |
| Mar. 5 | - discussed how much difference could have been due to error in measurement with the light meters (± 2)<br>- summarized / compared group results; discussed patterns, results that did or did not make sense with respect to different theories of current-flow |
| Mar. 6 | - Rachel and Rebecca tested a collection of #41 and #48 bulbs to see if they wear out at differential rates and reported their results (no gradual progression from bright to dim) to the class<br>- assigned individual written assignment:<br>a) Circle results in any groups' charts that don't make sense; tell why.<br>b) Explain how Samantha, Carl, and Rebecca-style circuits work and tell why they work the way they do.<br>c) Write down your current ideas about how a battery works.<br>(Jordan, Carl absent) |
| Mar. 9 | - continued work on individual assignments<br>(Rebecca was sick and left part-way through the period) |
| Mar 11 | - Frank shared his battery model (two-way crashing current); class discussed and debated his ideas<br>(Rebecca, Matthew absent) |

| | |
|---|---|
| Mar 16 | - discussed how to improve argument strategies from last day<br>- continued discussion of battery theories: Andrea presented her one-way current model as an alternative to Frank's one-way model |
| Mar 16 | - Frank's battery interview |
| Mar. 20 | - reflected on productive and non-productive elements of the previous day's class (some had watched a videotape of this class over the lunch break)<br>- watched videotaped Mar. 16 class<br>- compiled lists of what helped and what didn't help facilitate the development of ideas (completed Mar. 24 at beginning of math class) |
| Mar. 25 | - discussed students' perceptions of chemistry (introduction to chemistry unit)<br>- students mixed vinegar and baking soda and drew pictures of what they thought they would see happening if they could see the tiniest pieces of the substances<br>- demonstrated ability of vinegar and baking soda reaction to put out a candle flame |
| Mar. 25 | - Carl's battery interview |
| Mar. 26 | - Robert's battery interview |
| Mar. 30 | - discussed the summarized list of things that did and did not help the development of ideas (see Appendix F)<br>- spent most of the class discussing the role that books and other information sources should play in the construction of personal understanding |
| Mar. 30 | - Samantha's battery interview |
| Apr. 1 | - distributed information on electricity, chemistry<br>- students developed initial explanations regarding what happens when you mix vinegar and baking soda<br>- students reminded to anticipate others' questions and encouraged to use the distributed information if they so wished |

| | |
|---|---|
| Apr. 1 | - Keith's second battery interview |
| Apr. 3 | - distributed summary of unsolved puzzles (see Appendix D.4)<br>- discussed student-selected points in the summary; most of the discussion focused on divided vs. undivided batteries and the nature of and role of electrons<br>- some students used information from reference books to contribute to the discussion |
| Apr. 6 | - discussed / debated "What is energy?" |

### D.2. Student-developed circuit diagrams.

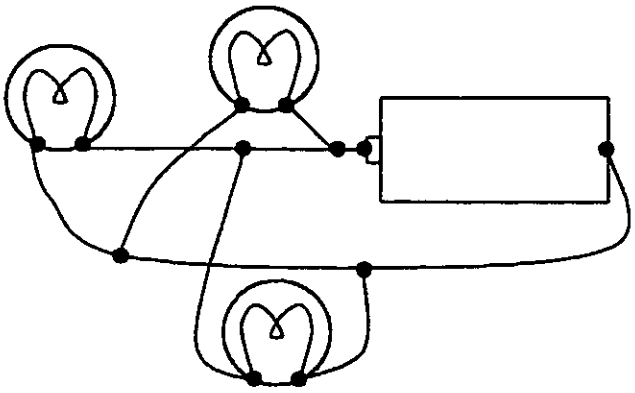


*Figure 5.* **Rachel-style circuit.**

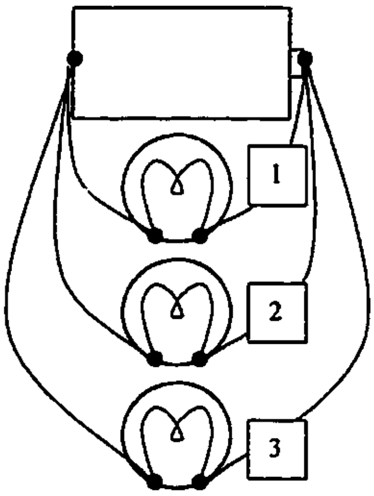


*Figure 6.* **Samantha-style circuit.**

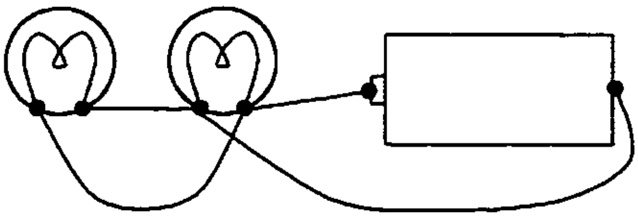


*Figure 7.* **Rebecca (A)-style circuit.**

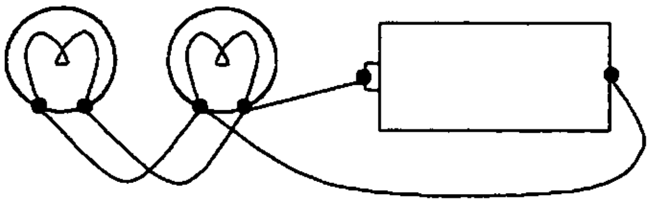


*Figure 8.* **Rebecca (B)-style circuit.**

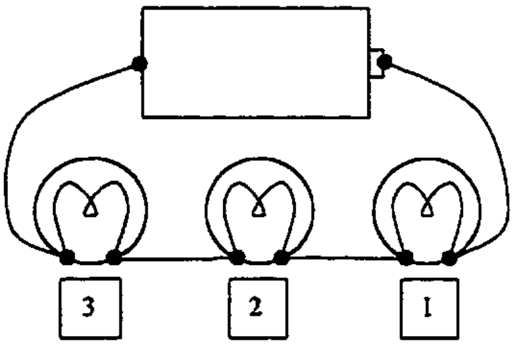


*Figure 9.* **Rebecca (C)-style circuit.**

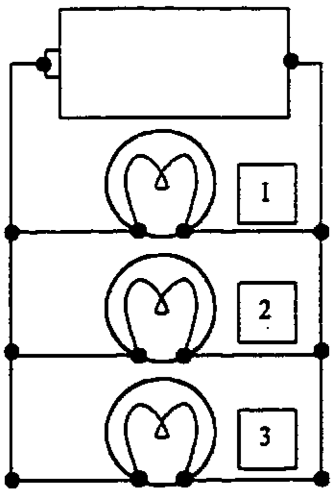


*Figure 10.* **Carl-style circuit.**

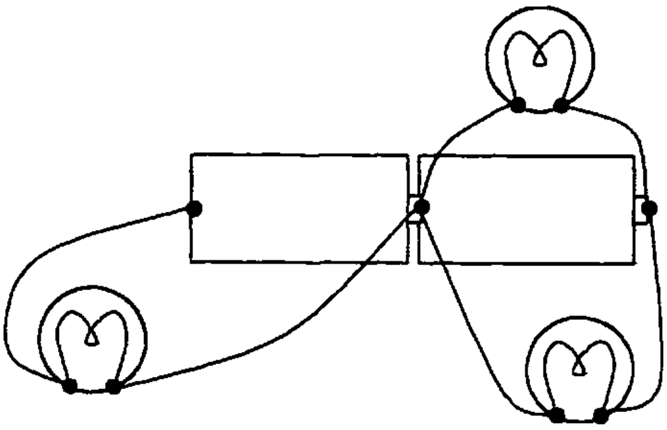


*Figure 11.* **Frank (A)-style circuit.**

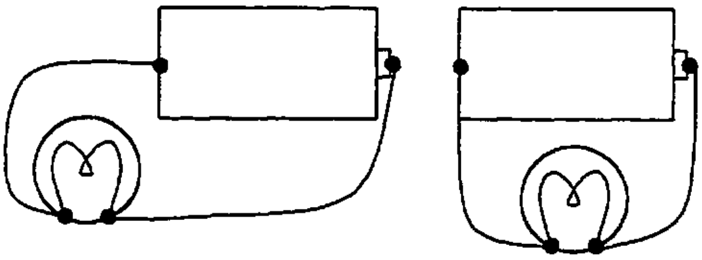


*Figure 12.* **Frank (B)-style circuit.**

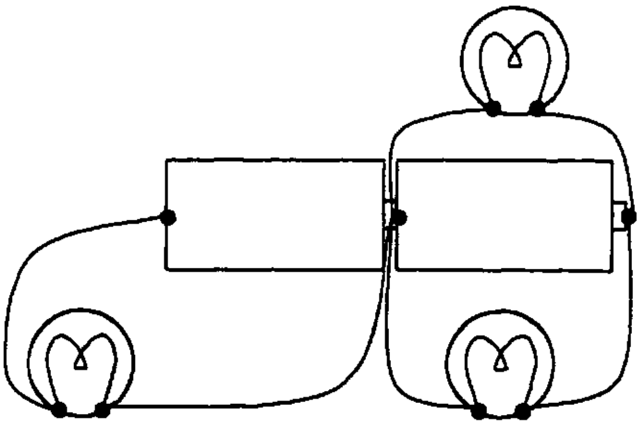


*Figure 13.* **Frank (C)-style circuit.**

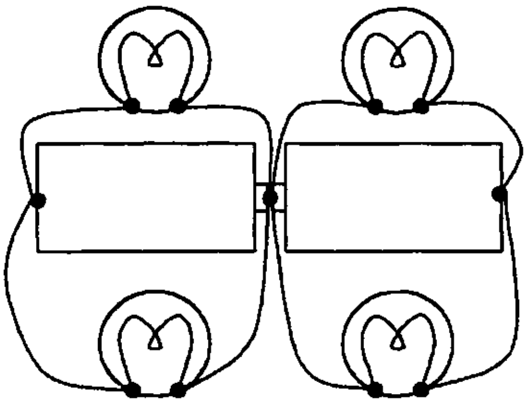


*Figure 13.* **Frank (D)-style circuit.**

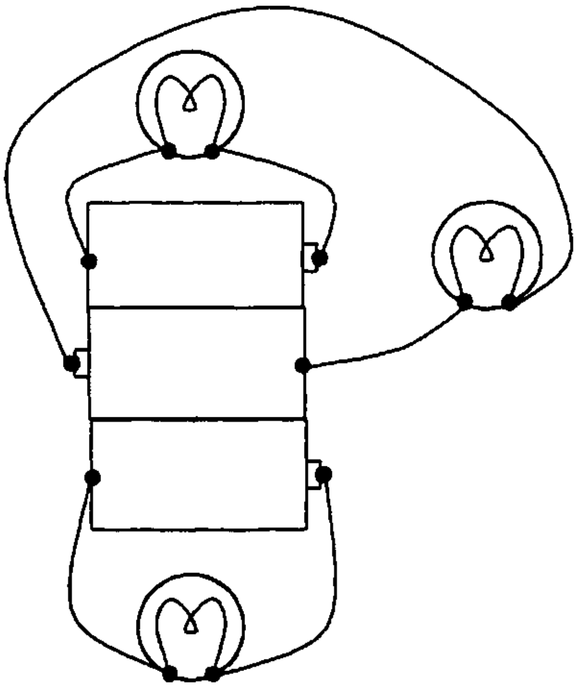


*Figure 14.* **Frank (E)-style circuit.**

D.3. "Thinking about Thinking" handout.

# Thinking about Thinking

## 1. General Background

- What are your favorite things to do in your spare time?
- What kinds of things do you do to help out your family or neighbors?
- What was your most memorable vacation? Why?
- What was the best idea that you've ever had? How did you get it?
- What is something that you've always wondered about? Why does it puzzle you?
- What do you know the most about? How are you able to remember so much?
- How do you feel about arguing with other people? Why?
- What was the hardest thing you've ever figured out? How did you do it?
- If you could change one thing about the world, what would you change? Why?

## 2. Thoughts During Classroom Discussion

- Why do you ask?
- What made you think of that?
- Do you have any other ideas?
- What do you think of ___'s idea? Why?
- Which theory(ies) / ideas make the most sense to you? Why?
- Which theory(ies) / ideas don't make sense to you? Why?

## 3. Thinking Back on Class Discussions

- What made you wonder about . . . . ?
- What made you think of ...?

- Which theory(ies) make the most sense to you? Why?
- Which theory(ies) / ideas don't make sense to you? Why
- Which theory(ies) / ideas are you certain are false? Why?
- Do you have a different idea that hasn't been suggested yet?

### D.4. Summary of battery arguments.

Note: I added arguments marked with a "*." The others were identified by one or more students during class discussion.

# Unsolved Puzzles

## How Does Electricity Move Through the Wires and the Bulbs?

## One-Way Electricity Models

### Model A: Divided

- Real batteries don't have dividers (e.g. the ones we took apart, the lemon, the wet cell).
- If one side of the divided battery is empty, hooking a wire from the positive terminal of one battery to the negative terminal of another should cause the bulb to light. It doesn't.
- If everything is used up in the bulb, why would you need a second wire?

### Model B: Non-Divided

- If the energy is created by mixing chemicals, why doesn't the battery use up all of its energy before it is connected?
- If particles are coming back into the battery, why does the battery run out? (only used particles are going back to the battery)
- If no particles are coming back into the battery, why do you need the second wire? (used particles are coming back into the battery)
- If no particles are coming back into the battery, why would packing be a problem? Wouldn't the space created by the particles that left make room for new ones from another battery?*
- If energy is used as it goes through the bulb, how would you light two bulbs in a Rebecca-style circuit?
- If everything is used up in the bulb, why would you need a second wire?

## Two-Way Electricity Models

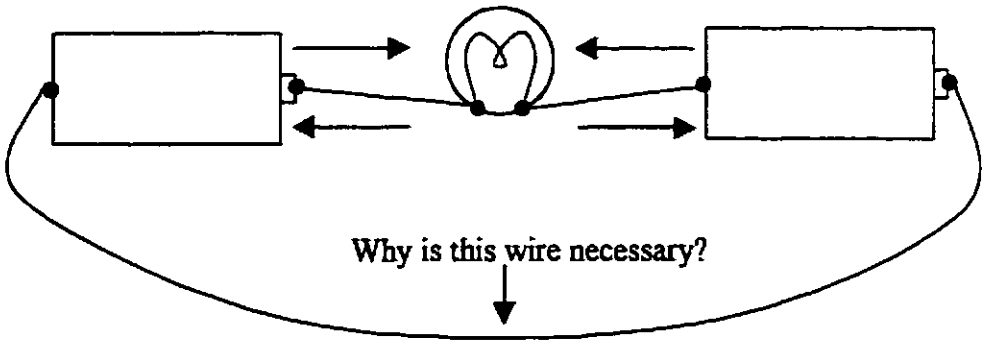
### Model A: Different Substances Crashing

- Why don't you get a hot wire between two bulbs hooked up Rebecca-style [in series]? (tunnels, not enough particles to crash often)

- The idea of tunnels creates several puzzles of its own:
  - If wire is full of tunnels, how do particles crash in the bulb's wire to create heat and light?
  - If wire is full of tunnels, how would you get a hot wire? (mixing of particles in negative side of battery; heat is transferred by conduction)
  - If hot wires are created by conduction from the battery, how would a high resistance wire in the middle of a circuit get hot when the wire to the battery does not?
  - If heat is transferred by conduction, then why doesn't the wire from the light bulb heat up the wire around the bulb?* (insulation)
  - If wire is full of tunnels, how could you connect two pieces of wire? How would you line up the tunnels? How would particles know which tunnel to go into? (magnetic tunnels)
  - If tunnels are magnetic, why isn't the wire attracted to a battery?
  - How do the tunnels get there?

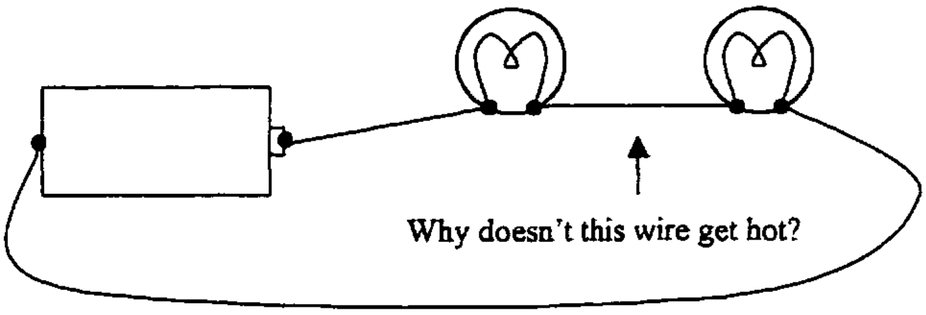
- If particles ("marbles") remain in the wires after the wires are disconnected from the battery, some wires should be left with positive particles and others with negative particles. If a negative wire is later connected to the positive terminal of the battery, why does it still work to light the bulb? (shocks or new particles switch them all to the kind that they need)

- If energy comes out of one side of a battery and used energy goes back into the same side, then why couldn't you hook one side of the bulb to the positive terminal of one battery and one side to the negative terminal of another battery? Why would you need a second wire to prevent packing?* (see diagram below)



**Model B: Same Substance Crashing**

- Why don't you get a hot wire between two bulbs hooked up Rebecca-style? (tunnels, not enough particles to crash often)



- If the same substance is coming out of both sides of the battery, you should be able to light a bulb by hooking both wires to the positive side of a battery. You can't. (positive side has more energy than the negative side)
- Again, why is a second wire necessary to prevent packing when you hook up a bulb between the positive terminal of one battery and the negative terminal of another?

## What is Energy?

**Model A: "Energy is a Particle"**

- If energy is a particle, then what kind of particle is it?
- How does it move through wire?
- What happens to the energy after it lights the bulb?

**Model B: "Energy is Something Particles Have" Model**

- If energy isn't the particle itself, then what is it?
- If particles just keep going back into a non-divided battery after giving up their energy to light the bulb, why don't they just keep going around and around? (battery runs out of energy so it can't keep giving more to the particles)
- If particles give up their energy to light the bulb, where do they go from there?

**Model C: "Energy is Something Particles Make" Model**

- How do particles make energy?* (friction)
- What is the energy? (heat and light)
- If particles just keep going back into a non-divided battery after creating the friction needed to light the bulb, why don't they just keep going around and around?
- If particles crash to create friction, heat energy, and light energy, then where do the particles go from there?

## How are Heat and Light Generated?

### Model A: Heat / Light from Mixing Chemicals

- What prevents the chemicals from mixing and using up all of the energy before you want to use the battery?
- How would chemicals travel through wire to mix in a light bulb?
- If the chemicals are separated, what does hooking up wire do that allows them to mix?
- If the chemicals create heat and light when they are mixed in the bulb, why don't they when they are mixed outside the bulb?*
- Real batteries don't contain two acids. They only contain one type of liquid, and it's not always an acid (sometimes it's a base, sometimes it's something else).*
- In the wet cell, the fizz was forming on one of the pieces of metal (electrodes) that were sitting in the hydrochloric acid. The piece of metal appeared to be getting used up.*
- Some people were talking about the energy getting hard after it was used. Why is this necessary? Also, it didn't happen in the wet cell or the lemon.*
- Why are two different kinds of metal needed in the wet cell and the lemon to make it work?*

### Model B: Heat from Friction

- Why does copper wire, which has more room than light bulb wire, get hot when you hook it from the positive to negative end of the battery with no bulb in between?
- If the heat is created by friction, what are the reactions inside the battery for?*

# APPENDIX E

## Progression of Activities in the Chemistry Unit

1. Timeline.

**E.1. Timeline.**

| Chemistry Timeline | |
|---|---|
| Mar. 30 | - discussed summarized list of things that did and did not help the development of ideas (see Appendix F)<br>- spent most of the class discussing the role that books and other information sources should play in the construction of personal understanding |
| Apr. 1 | - distributed information on electricity, chemistry<br>- students developed initial explanations regarding what happens when you mix vinegar and baking soda<br>- students reminded to anticipate others' questions and encouraged to use the distributed information if they so wished<br>(Rachel, Jennifer absent) |
| Apr. 6 | - discussed "What is energy?"<br>- continued individual investigations |
| Apr. 8-19 | (no school) |
| Apr. 20 | - shared results of investigations, discussed explanations for the vinegar and baking soda reaction<br>- continued individual investigations<br>(Rachel absent) |
| Apr. 22 | - discussed points for lists of things that helped and didn't help class discussion<br>- shared results of investigations, discussed explanations for the vinegar and baking soda reaction<br>- briefly continued individual investigations |
| Apr. 24 | - spent most of the period reading from information distributed on Apr. 1<br>(substitute teacher) |

| | |
|---|---|
| Apr. 27 | - discussed sources of ideas and questions<br>- shared results of investigations, discussed explanations for the vinegar and baking soda reaction<br>- continued individual investigations |
| Apr. 29 | - video-based reflection: What kinds of ideas and questions do people use? |
| May 4 | - continued individual investigations<br>(Jennifer absent) |
| May 5-8 | - alternative activities pertaining to a different topic<br>(Samantha, Carl absent; substitute teacher) |
| May 11 | - required writing time for ten minutes<br>- continued individual investigations |
| May 13 | - shared results of investigations and discussed explanations for the vinegar and baking soda reaction<br>- continued individual investigations |
| May 15 | - shared results of investigations and discussed explanations for the vinegar and baking soda reaction<br>- provided students with the names and chemical formulas of a variety of common acids and bases |
| May 15 | - Keith's chemistry interview |
| May 20 | - continued individual investigations |
| May 22 | - distributed handout pertaining to the roles of baking soda and baking powder (no discussion; students were asked to put it in their binders)<br>- shared results of investigations, discussed explanations for the vinegar and baking soda reaction<br>- continued individual investigations |

| | |
|---|---|
| May 25 | - shared results of investigations, discussed explanations for the vinegar and baking soda reaction<br>- continued individual investigations |
| May 25 | - Carl's chemistry interview |
| May 28 | - Samantha's chemistry interview |
| May 29 | - Robert's chemistry interview |
| June 1 | - reviewed for final exam |
| June 3 | - continued individual investigations |
| June 5 | - Grade Sixes completed a practice final exam<br>- Jordan, Jennifer, Rebecca continued investigations |
| June 5 | - Frank's chemistry interview |
| June 15 | - culminating discussion (partial solution to the vinegar and baking soda puzzle) |

# APPENDIX F

## Things that Worked and Didn't' Work

## During Class Discussion

1. Original list.
2. Modified list.

### F.1. Original list.

**Helped**

1. examples (magnets)
2. cooperating to take turns
3. diagrams
4. previous arguments
5. zoom-in feature of the camera
6. organized binder notes
7. new ideas
8. putting up hands + jumping in
9. Arguments bring out more things.
10. Ms. S. jumping in **with questions**
11. the history story **(Thomas Edison)**
12. chalkboards
13. testing things
14. lots of questions
15. stay on one battery
16. 10 sec. or 5 sec. rule for jumping in
17. **actions**
18. **idea page**
19. **using your own knowledge**
20. **staying on topic**
21. **dictionary**
22. **support each other's ideas**

**Didn't Help**

1. noise in background
2. talk in camera is too loud **(Ms. S.)**
3. saying questions twice
4. keep on saying questions without answers
5. interrupting
6. too many people doing too many things
7. speak louder
8. top of the head arguments
9. out-of-argument problems that can be easily solved
10. teacher butting in
11. props in the way
12. use props where people can see
13. talking to yourself
14. say one question to more than one person
15. walking in front of the camera
16. **Sometimes your own knowledge doesn't work**

**F.2. Modified list.**

**Helped**

1. examples (magnets)
2. cooperating to take turns
3. diagrams
4. previous arguments
5. zoom-in feature of the camera
6. organized binder notes
7. new ideas
8. putting up hands + jumping in
9. Arguments bring out more things.
10. Ms. S. jumping in with questions
11. the history story (e.g. T. Edison)
12. chalkboards
13. testing things
14. lots of questions
15. stay on one battery
16. 10 sec. or 5 sec. rule for jumping in
17. action explanations
18. idea page
19. using your own knowledge
20. staying on topic
21. dictionary
22. support each other's ideas

**Didn't Help**

1. noise in background
2. talk in camera is too loud (Ms. S.)
2. saying questions twice
3. keep on saying questions without answers
4. interrupting
5. too many people doing too many things
6. speak louder
7. top of the head arguments
8. out-of-argument problems that can be easily solved
9. teacher butting in
10. props in the way
11. use props where people can see
12. talking to yourself
13. say one question to more than one person
14. walking in front of the camera
15. Sometimes your own knowledge doesn't work / Think before you answer.

# APPENDIX G

## Student Interaction with Textual Material

### G.1. Using books to develop an understanding of electricity.

In Chapter Two, and again in Section 4.2.2.4, I suggested that there is no need to separate a context of justification from a context of development when approaching science education. Here, I would like to reinforce this idea with the help of some very telling dialogue that took place near the end of the electricity unit. The students had just spent several class periods discussing whether books should play a role in the development of their theories, and agreed to try them out. Although they did not reach fully accurate conceptions of the manner in which current flows through an electrical circuit by the end of this activity, they collectively demonstrated a remarkable willingness and ability to ask questions of the textual material with which they were dealing. Much of the information dealt with very abstract conceptions of matter, and the students' understandings progressed in some very interesting ways over the course of the discussion. The questions that remained with them at the end of the unit are rooted in what could be a very motivating theoretical base from which to develop still deeper understandings of the nature of electricity, and ultimately, the nature of matter.

During the April 3 class discussion, Robert made the following references to materials that he had been reading:

Matthew: Because batteries don't light up, and they create energy.

Robert: They make electrons.

Ms. S.: What makes electrons?

Robert: The powdered zinc and the electrolyte.

Ms. S.: Are you guys paying attention?

Robert: The powdered zinc and the electrolyte makes, uh....

Ms. S.: Can you explain those terms, because they're not terms we've used before.

Robert: Here's a picture. It's like chalk bits.

Ms. S.: It's like taking one of these and crunching it, or what?

Robert: I'd say that. And electrolyte is a liquid.

Ms. S.: So in here [the wet cell on display in the classroom], what would the electrolyte be?

Class: The water.

Robert: And the Drano would be the zinc.

Ms. S.: So then what are these [the electrodes]?

Robert: That is the conductor.

Ms. S.: To conduct what?

Robert: To conduct the electrons.

Ms. S.: And what are electrons? You guys can jump in with these questions, too.

Robert: I don't know. I haven't read that.

Rebecca: On the back of "Back to Basics" it tells you what an electron is and the ion is. There's some pages on that.

Ms. S.: And can you explain it?

Rebecca: Well, I haven't read that much yet.

Although Robert's initial comment did not demonstrate in-depth interaction with the new ideas he was reading about, subsequent questioning helped him to probe deeper, and the rest of the class soon became collaboratively engaged in finding out more about the role of electrons in an electrical circuit. It is significant that all class members spontaneously contributed to this discussion. Further samples of the students' willingness to question the text and to build ideas based on information from different sources are presented in the excerpts that follow:

Robert: The electrons are smaller than the atoms, and these ions are what-

Rebecca: Normally, an atom has an equal number of electrons and protons.

Robert: From what I get, when you put a positive ion and a negative ion, that's what I think makes the electricity.

Ms. S.: How do you get that, Robert?

Robert: "When an atom gains one more electron, it becomes negative, and it's called a negative ion, and a positive ion results when an atom becomes positively charged. It is then called a positive ion" [reading from the book].

...

Andrea: Here for electrons on the first page of "Back to Basics," it says that free electrons can move at high speeds through metals, gases, and a vacuum, or they can rest on a surface. What does it mean "free"?

Ms. S.: Free electrons. It says free electrons can move? What do you think that that might mean? Anybody have a suggestion for Andrea? Rebecca?

Rebecca: Maybe there's one electron by itself, so it's free and not with a bunch of other electrons.

...

Rebecca: Okay, I've found something, and it's on the next page. It says: "'More About Free Electrons." Many trillions of electrons can rest on the surface or travel through space or matter at near the speed of light. And that's one-hundred-and-eighty-six-thousand miles per second."

Matthew: Wow! That is like VOOM!

...

Rachel: On some of these pages, can you highlight them?

...

Samantha: Like, free electrons, to me it sounds like they're little, sort of like atoms.

...

Keith: Electrons, I think, are electricity, because if you look on "Back to Basics," it has a lithium atom, and if you look at this lithium atom at the top, it has three electrons on it with the minus sign on them, so in the free electrons, I think the electricity is just going anywhere.

As the discussion continued, the students identified ways of getting answers to the questions that they ask of books:

| | |
|---|---|
| Ms. S.: | .... So if you could ask this book a question, you would say- |
| Class: | What do you mean? |
| Ms. S.: | The only problem is, can the book answer? |
| Class: | No. |
| Ms. S.: | So, if we have that question, what might we do with it? You could ask somebody else. You could ask the teacher. What if the teacher wasn't there? |
| Rachel: | If you track it down in the book and the person who wrote it, then you could ask the person. |
| Ms. S.: | Is that probably an easy thing to do? |
| Class: | No. |
| Ms. S.: | To find the author? You might with the Internet. That might be one way to go about it. |
| Robert: | Or maybe you could just look in a different book, and then maybe it's a book from one big company. |
| Ms. S.: | Do different books explain things in different ways? |
| Class: | Yes. |

The following set of excerpts are interesting in that they portray students making active attempts to identify differences between graphical representations of a model and the entity it is intended to represent:

| | |
|---|---|
| Jennifer: | Like, the extra electron is negative, and the missing electron is positive. Why would it be that way? |

Ms. S.: Samantha?

Samantha: See, right here? This is an electron right here [showing Jennifer a diagram in her book]. So if it has a minus sign on it, then it means it's um.... It's a negative ion. Okay, so if it has a little mark there, that's a negative ion. Do you see what I'm saying? And if it's missing the mark, then it's a positive ion. So, maybe these little things, wherever they are - the electrons - maybe they have, um.... If you take one and stick it under a microscope or something, maybe they have a little sign on them or something. Like, maybe just a little red mark or something. And that could be the extra electron.

Ms. S.: So, electrons are little red marks? Is that what you're saying?

Samantha: No. It says to make it a negative ion, it has to have that mark on it, right?

Ms. S.: What mark?

...

Samantha: See this right here? If it's a negative ion, it has to have that mark on it.

...

Samantha: Yeah, so if, in real life, I don't think that if you could see an ion, I don't think it's going to have a little negative sign on it.

...

Robert: Uh, in this book that I have, it has that there's five different little dots running around on the ring. So then, if you're missing one, well then you know that it's a positive ion because it's missing one. And then if you have six on one, then it's a negative.

Samantha: I don't get what you mean.

Robert: If you saw it under a microscope, you won't see the minus sign, but you would see more than one.

The next collection of excerpts document Frank's efforts to determine why ions attract electrons. His persistent questioning of such abstract matters is particularly interesting in light of the fact that Frank is often described as a student who is "unfocused", "doesn't pay attention in class," and who is not a "book-learner." It is interesting that he is also a student who in many cases tended to use isolated-case reasoning. His questions in this context are particularly remarkable in contrast to these observations:

Frank: Moving electrons. "A stream of moving electrons is called an electrical current. Resting electrons can quickly turn into an electrical current. If placed near a cluster of positive ions, the positively charged ions will attract to the electrons, which will rush in to fill the holes or voids" [reading from book].

Ms. S.: Voids are empty spaces, right.

Frank: Left by the missing electrons. So why do the ions attract to the electrons?

Ms. S.: Okay, what are the ions attracting to?

Frank: To the electrons.

...

Ms. S.: Any thoughts on that?

Robert: It says that missing electrons are caused by mechanical friction. "Light, heat, or chemical reactions will move electrons from a positively charged surface. This causes the surface to be positively charged." It says that the positively charged atoms are at rest, then the surface can be said to have an electrical charge. So then, if there is no mechanical friction, light, heat, or chemical reactions, that could be how more can get on.

Samantha: So, you're saying that.... Do you want to say that again?

...

Frank: So mechanical friction, light, heat, or chemical reactions will move electrons to the surface, right? So, why do you need light, heat, or chemical reactions to remove an electron?

Robert: Because nothing else can remove them.

Frank: So, why do you have to remove them?

Robert: You don't. We can't prevent them from taking them away an electron.

...

Frank: So, the positively charged ions will attract electrons, and they will rush to fill the hole. So, why does ions attract the electrons?

...

Frank: So, an ion is one of those big round things? And then the electrons are the things that move around it.

Ms. S.: Okay. And Robert mentioned the ions moving around. Does the whole ion zoom around or just the electron?

Robert: Just the electron, but then it would all stay in one place.

Ms. S.: The ion or the electron?

Robert: The ion.

Samantha and Robert's attempts to visualize the difference between ions and electrons demonstrate a powerful strategy for sense-making:

Samantha: Can't these little guys move on these while this thing is moving? Pretend the classroom is an ion. We're all electrons. If I'm running around the classroom, the classroom isn't moving.

Robert: We don't know. The floor's vibrating, right? We can't see it move, but-

Samantha: But can't you have this thing stay still and these things move? Like that thing can vibrate, but it doesn't have to go from here all the way over there to [nearby town].

Robert: Then how would you get atoms into here? Like, if somebody.... How do I get atoms into here if they don't move?

Samantha: They don't have to stay still, though.

Ms. S.: What do you mean, Robert? Get atoms into where?

Robert: Here. Into my ruler.

Ms. S.: How are you getting atoms into there? I'm not sure. I don't understand the question.

Robert: Well, she said that the atoms stay still, and if they're in my ruler, then they will –

Ms. S.: But aren't they in there? Are there atoms jumping out of your ruler?

Robert: No.

Ms. S.: That's what I mean. I'm not sure what your question is.

Samantha: I think he's asking how atoms got into his ruler if they can't move.

Ms. S.: Do you mean they don't move by themselves?

Samantha: I don't mean that they don't or that they do move. I'm just saying that Robert said that we were asking which one moves, and I was trying to make a point that these can move.

Robert: That's what I would say, too.

Samantha: These can move, but this can also move, or it can stay still.

Ms. S.: So, even if that's still, the electrons could still be moving? But it could move if you wanted it to move? If this whole classroom suddenly took off and was flying through the air with us in it, could we still run around the classroom?

Class: Yeah.

Ms. S.: So, could they both be moving?

Class: Yes.

Ms. S.: But could this stop and these keep on moving?

Samantha: Like, there could be an atom right in front of my face right now, and he could be standing still, but if I go like that [swipes the air], he's going to start moving.

As the class period drew to a close, Frank resumed his questioning, this time making explicit reference to the battery arguments of previous discussions and thereby demonstrating his attempts to integrate new information with the old:

Frank: Robert said that whenever you shut off the battery, right, that this becomes an ion and the electrons attract to it. Right, Robert?

Robert: No, they attract to the metal piece inside of the battery. The metal in the middle.

Frank: So they would attract to this, right?

Robert: No. They attract to that.

Frank: So, why do they attract to here? Is there some kind of force attracting them?

Robert: Yes.

Frank: A nail doesn't have force.

Robert: Yes, but there's other stuff inside of the battery.

...

Keith: Wouldn't you think there are atoms in your hand? Like, your hand is made of atoms?

Class: Yes.

Frank: So, like in a battery, when we were doing our battery arguments, right. The energy would come through here and then go out into the wire. So, when the battery is running, wouldn't it attract the energy or the ions?

Ms. S.: So, Frank, are you saying that energy is ions?

Frank: Electrons.

Ms. S.: Oh, electrons. Is everyone agreed on that, or is everyone saying that the electrons are the energy?

Class: Yes.

Keith: I think the electrons are energy.

Ms. S.: The electrons are energy or make energy?

Keith: Are.

Ms. S.: Electrons are the energy, or they make the energy?

Keith: They are the energy because what would be energy? What would be the energy? There has to be something to be the energy.

Frank: And to finish my question, the ions are in here, the energy - They want to get out of the battery, right?

Ms. S.: When you say energy, Frank, what are you talking about?

Frank: Well, the electrons. The electrons want to get out, right? So wouldn't they be attracted to that all the time? Because they want to get out, so they come here and they'd all be rushing to get out.

The material with which the students dealt in this passage is difficult. However, the manner in which they interacted with such complex ideas is quite remarkable.

# APPENDIX H

## Further Discussion of FOI

1. Issues arising from attempts to define FOI levels.

2. Connections between students' beliefs about science and their approaches to science.

3. Focused vs. free exploration.
    3.1. Foundational activity.
    3.2. Conscious diversions.

4. Clearly articulated, theory-based, and off-topic.

5. Technology-based activity.

### H.1. Issues arising from attempts to define FOI levels.

Because my own initial confusion between the epistemological status of what I have termed "vague" and "specific" theories and "internal" and "external" variables acted as a serious impediment to defining the difference between Level 2 and Level 3 FOI, it may be helpful to provide a brief description of the evolution of these categories. As will be demonstrated, Henriques' (1990) categorizations are similar to my original ideas and display some of the inconsistencies that I initially struggled with.

In the early stages of developing the FOI framework, I emphasized what I called "clue-gathering" as a defining characteristic of Level 2:

> The student is focused on identifying component parts and isolating them to determine their role in the phenomenon that he or she is attempting to explain. At Level 2, this is primarily a random-selection process in that it is unguided by a broader theoretical framework, and activities are often driven by a "vague theory" which may be prefaced with, "It has something to do with...."

A specific theory, or one in which a phenomenon is explained in a holistic manner that attempts to describe the role of salient variables, was included as a higher-level FOI strategy. This division is not supported by the current definition. Although the distinction between vague and specific theory remains valid, both may drive theory-based investigation, and, as shall be shown, both are consistent with Level 3 FOI. A vague theory is one that identifies a variable as a potential causal factor without describing how the variable interacts with other elements deemed salient to that phenomenon. It may be used in the service of Level 3 inquiry provided that its connection to the focus question is made apparent. Both vague and specific theory may serve Level 2 effect-seeking if it is not.

An initial distinction between external variables used in effect-seeking and internal variables used in clue-gathering also proved untenable in its original form. Originally, external variables were defined as variables not present in the original phenomena and that could therefore drive only WWHI investigations that focused on using tangential stimuli to cause some sort of response. When properly grounded in a theoretical framework, however, variables that would have been classified as external by this definition may in fact play a significant role in Level 3 investigation. For example, substituting various substances for vinegar in the vinegar and baking soda reaction involves the introduction of stimuli external to the original reaction. If this is merely done in the hopes of generating an effect, the new substances are indeed external variables in that nothing about them is hypothesized as salient. However, if they are introduced as a means of determining whether vinegar has a special property that is salient to the reaction, such as by testing the effect on the reaction of substances with different pH levels, the new substances are being used as a focused means of manipulating a hypothesized internal variable. Definitions for internal and external variables have been clarified to emphasize the dependence of their classification upon the theoretical basis that defines them:

1. internal variable: a variable with a hypothesized or demonstrated causal role in the phenomenon being investigated
2. external variable: a variable which may be shown to affect the phenomenon, but with no hypothesized or demonstrated causal role in the phenomenon being investigated

By these definitions, a distinguishing factor between Level 2 and Level 3 FOI is that Level 2 deals with external variables, whereas Level 3 deals with internal variables.

Careful analysis of Henriques' (1990) work has made apparent interesting parallels between her work and the current study. These are particularly interesting when the differences between the guiding frameworks which motivated their delineation and those driving my own categorizations are taken into consideration. As discussed in Section 4.3.1, the four identified approaches to inquiry identified in this study are defined according to the nature of the guiding theoretical frameworks upon which the students' investigations, be they rational or empirical, are based. By contrast, Henriques categorized student activity according to whether it focuses on the activity of the child, the objects of investigation, the outcome of the investigation, the results derived from the child's actions, the results derived from the nature of the objects, or combinations of these. Most of her descriptions of spontaneous activity-types are consistent with those observed in this study, but many of her categories seem redundant. Re-classifying her activity-types into the categories I have described clarifies the nature of my own categories and provides further evidence for student activity at each of the levels of inquiry identified here.

Henriques classified "activities that focus on the action of the subject, on the object or on the result" in Category A, "activities through which the child seeks to single out the factors that have contributed to a particular result; which steps contributed to it and the role the objects played in it" in Category B, and "activities that are experimental" in Category C (p. 61). These categories differ markedly from mine in that activities in her category a and category b may be used at Level 2, Level 3, or Level 4 FOI. A carefully controlled experiment (Category A) aimed at investigating a hypothesized effect generated by a variable external to the focus question contributes little to the development of integrated knowledge of a particular phenomenon. Conversely, determining whether and / or how a certain variable contributes to a phenomenon (category b) can make significant contributions and may be done experimentally. This may be seen in the case of determining whether pH plays a causal role in the vinegar and baking soda reaction by testing baking soda with various other substances of known pH.

As described, Henriques' Type 3 activity is not specified in a manner that allows it to be classified into my scheme, and in fact overlaps with others of her own categorizations. As a child "tries to understand how something works and chooses to explore objects found in the material provided" (p. 160), the approach he or she takes may involve the application of various stimuli or may involve theory-based experimentation.

Henriques' Type 1 activity is the only one in which the student is unable to articulate the intent of his or her activity. From a theoretical standpoint, this sets it apart from the others, and, although it was not observed in this study, forms part of a basis for the hypothesized Level 1 FOI.

Type 2 activity describes that in which the student is "bent upon obtaining a particular result and all his actions are done with this aim in mind" (p. 159). Although the student may have clear intent in mind, he or she is motivated by technological rather than inquiry-based goals. Due to the lacking theoretical base, this type of activity is characteristic of Level 2 FOI. It is unclear how Henriques' Type 2 activity differs from Type 5, in which "The child tries to obtain a given result by varying his actions" (p. 160).

Henriques' description of Type 4 activity completes my profile of Level 2 FOI in its description of effect-seeking with no preconceived intent: "The child attempts to establish a relationship between the product and the process or the sequence of actions performed. When asked to explain what he is doing, he often replies, 'I want to see what happens'" (p. 160). The child's hesitance to make predictions despite expectations regarding what should happen may be indicative of the nature of his or her goals: Being right or wrong is not an issue. The goal is to create an effect, not to test an idea.

Although the difference between "What would happen if I applied Stimulus *S*?" (based on an unstated expectation of Response *R*) and "How can I achieve Response *R* by means of Stimulus *S*?" may appear inherently semantic, one falls within a sequence of activity that involves troubleshooting to reach a final effect, and one in a sequence aimed simply at finding out what happens. Despite this difference in intent, their common lack of theoretical guidance places both at Level 2 FOI.

Henriques' Type 6 and Type 8 activity are not adequately distinguished by emphasis on the experimental nature of Type 8. She describes Type 6 as follows:

> In an effort to determine the role of the object in obtaining a given result, the child tries to reach the same result by varying the objects used. For example, seeing that froth forms when vinegar and sodium bicarbonate are mixed together, he tries to mix in other powders like flour, sugar, or salt and to replace the sodium bicarbonate with one of them. He also tries a substitute for vinegar by mixing sodium bicarbonate with methylated spirit. (p. 160)

If the child was in fact attempting to determine the role of the vinegar or the baking soda by undertaking such activity, it could be argued that he or she was testing a vague hypothesis such as: "It has something to do with the baking soda" and that his or her activity was in fact experimental. However, that baking soda plays a role of some sort is obvious, and likely the child was merely applying a new stimulus to other familiar phenomena in an attempt to achieve an effect. If so, the child's activity exemplifies Type 4 activity in that he or she is using a stimulus known to be effective in one situation (the baking soda) in an attempt to generate responses in other situations. This example would be classified at Level 2 FOI in my categorization.

In the current study, attempts to determine the effects of distilled vs. normal water or the effects of adding different types of salt to the vinegar and baking soda reaction were usually classified as Level 2 FOI in that they involved the addition of new variables just to see what would happen or in the hopes of effecting something interesting. Vinegar worked, so why not salt? Well, why not salt? Or why salt? Reasons for similarity have not been identified, denigrating the status of salt to that of external variable. Finding out that salt has an effect on the reaction between vinegar and baking soda does not contribute to understanding of that reaction. By contrast, one student tested the effect of adding salt based on the hypothesis that if vinegar and baking soda react to make a certain type of gas, vinegar and salt should make a different type of gas, because different particles are involved. This demonstrates Level 3 FOI: Because of the way this student prefaced her activity, her results will provide information that is directly connected to the guiding question. Testing vinegar with a variety of other substances with a hypothesized causal factor (e.g. compounds that contain sodium), also reflects a more focused attempt to determine what is doing the reacting. The relevance of these activities must always be judged by the way that the students define their investigations in relation to the guiding question, in this case, "Why do baking soda and vinegar react in the manner that they do?"

Henriques' Type 8 activity is consistent with Level 3 FOI. She describes it as "qualitatively different from the preceding ones" in that "the course of action is chosen on the basis of an assertion that the child believes to be true and that he would like to prove to himself and others. The sequence of activities takes the form of clear logical steps in an experimental plan" (pp. 160-161). Type 8 activity is consistent with Level 3 FOI in that both are dependent upon a theoretical base.

The importance of context in distinguishing different types of student activity is apparent in the following example, which Henriques (1990) called Type 6 activity:

> A boy from the same group starts transferring water from one container to another by the same method [a straw with a finger held over the top] but instead of a straw he uses a thin plastic tube (by chance?). He is delighted with his success and soon abandons the idea of transfering the water. (p. 162)

Without a defined focus question within which to frame the child's actions, it is difficult to determine whether the boy's activity is aimed at testing a theory that states something like: "The tubular nature of a straw is the salient feature that allows the transfer of water in the manner described" (type 6 / 8 activity), a WWHI investigation that takes a known stimulus (a tube) and applies it in different contexts (type 4 activity), or an attempt to elicit a predetermined effect (type 5 activity).

Viewed in isolation, then, the types of activities performed by students working at Level 2 FOI may not differ outwardly from those of a student working at Level 3 or Level 4. Any of these may involve carefully controlled tests involving carefully chosen equipment and techniques, but activity involving controlled testing does not always denote sustained attention to the investigation of a particular topic. The difference between Level 2 and Level 3 FOI lies in the presence of a sustained framework which grounds activity, allows insights to be gleaned from it, and provides a theoretical web within which new information may be integrated.

None of Henriques' categories addressed Level 4 FOI. This is consistent with my observations of Grades Five and Six students, all of whom operated at either Level 2 or 3. My Level 4 criteria are primarily drawn from studies of experts, but are supported by evidence that some of the students observed advanced toward activity that mirrors the criteria identified as descriptors at this level.

### H.2. Connections between students' beliefs about science and their approaches to science.

Parallels between the identified FOI levels and work done by Carey et al. (1989) and Carey and Smith (1995) provide evidence of a reciprocating relationship between students' beliefs about science and their approaches to science, and the nature of this evidence implicates progression via conceptual change that is triggered by reflective abstraction. This view is consistent with Moshman & Lukin's (1989) "creative construction of rationality" (p. 183), but blends the inductive and deductive components of their work to reflect a more macrocosmic view of scientific thinking much like that described by Clement (1989b). This study supplies evidence that the manner in which students engage in scientific activity influences their beliefs about science as well provides evidence that their awareness of these beliefs further influences the manner in which they do science. This is exemplified in the conscious and systematic use of previously implicit strategies that several of the students made evident in comments shared during class discussions or individual interviews. As a point of clarification, Carey et al.'s (1989) Levels 1, 2, and 3 categories regarding children's beliefs about science roughly correspond with Levels 1, 2, and 3 in my FOI progression, which focus on their actual approaches to scientific activity. This is logical if consistent application of the criteria at a given level requires conscious awareness of the strategies involved. I have divided Carey et al.'s Level 3 criteria into two sections to reflect what appear to be very significant metacognitive differences between theoretically driven activity and activity which recognizes the theory-dependence of observation within such activity.

It seems likely that progression through Carey et al.'s levels is based on students' efforts to develop deeper understandings of the phenomena they are investigating, which in turn provides a context for reflective understanding of the nature of science. As Duckworth (1996) claimed:

> The pedagogical implications here seem to be fairly clear-cut: Teaching linguistic formulas is not likely to lead to clear logical thinking; it is by thinking that people get better at thinking. If the logic is there, a person will be able to find adequate words to represent it. If it is not there, having the words will not help. (p. 25)

In hindsight, it may seem rather obvious that approaches to scientific inquiry may only be consciously recognized after a student has actually engaged in them.

The stage of reasoning that a child demonstrates in one context may not indicate a more general or domain-independent stage of development. However, the nature of the activities defined within Level 3 or Level 4 FOI may include very preliminary explorations of phenomena if the information gleaned is related back to a focus question. The levels of inquiry define a manner of progression through levels of understanding which may be applied to very different content areas and which stand in contrast to the domain-specificity inherent in Piaget's descriptions of levels of thought:

> Piaget has speculated that some people reach the level of formal operations in some specific area that they know well – auto mechanics, for example – without reaching formal levels in other areas. That fits into what I am trying to say. In an area you know well, you can think of many possibilities, and working them through demands formal operations. If there is no area in which you are familiar enough with the complexities to work them through, then you are not likely to develop formal operations. Knowing enough about things is one prerequisite for wonderful ideas. (Duckworth, 1996, p. 14)

It is not enough to simply say that students will progress to higher levels of inquiry when they are developmentally ready to do so or that it is sufficient that they are capable of theoretically driven experimentation when working within a familiar domain. The ability to use certain strategies in unfamiliar domains is critical to the development of the criteria defined here. In the individual interviews, there were numerous occasions during which the students were able to answer questions at the level above which they typically worked independently, and when they could be guided to conclusions in this manner. The challenge, then, is to help students reflect on their experiences in familiar content areas in a manner that allows them to define broad metacognitive understandings that make it possible for identified strategies to be more broadly applied.

Carey and Smith (1995) questioned whether children's progression through the epistemological stages identified in the Carey et al. (1989) study is the result of conceptual growth or conceptual change:

> Domain-specific knowledge acquisition often involves large-scale reorganization and genuine conceptual change (Carey, 1989b, 1991). It is an open question whether a transition from Level 2 to Level 3 epistemology requires such a reorganization. The levels are not yet well enough characterized to even hazard a guess. (p. 47)

If Carey et al.'s levels regarding student beliefs about science are as closely related to the student approaches to science identified in this study as they appear to be, then evidence such as that provided here should provide at least indirect evidence that epistemological change indeed involves conceptual change. In fact, there is considerable evidence in the activities and discussions of the students that progression through the levels may involve the development of metacognitive understandings that essentially constitute conceptual change and which may not occur without direct challenge to prior metacognitive knowledge.

The Level 1-2 transition was not observed in this study, as none of the students observed started at Level 1 FOI. Prior to Level 3, students may interact with provided materials in a manner that does not require them to understand fully what is meant by "How…?" or "Why…?" However, by Level 3, sustained development of deeper levels of theory requires that they do pose questions such as these. The transition from Level 2 to Level 3 FOI also requires an understanding that all investigations must somehow contribute to an understanding of the broader question. This necessitates the recognition that a clear focus on the broader question is dependent upon the articulation of a theory with at least a minimum degree of specificity that may act as a basis for judging the relevance of proposed variables. The transition from Level 3 to Level 4 FOI is marked by an explicit understanding of the role that old theories play in the development of new ones, by the recognition of the need for attempts to disconfirm those theories in a systematic manner, and through the recognition that all knowledge is the product of theory-based construction. As students consider alternative explanations that may be shown to be quite plausible, they may experience a sense of relativistic futility during which the point of theory-development begins to appear quite hopeless. This was clearly demonstrated by Carl and is supported by evidence in the literature. The resolution of this state may occur as students develop an understanding of the need to attempt to disconfirm all theories rather than simply seeking evidence in their favor or altering them to fit existing evidence.

Carey and Smith (1995) stated the following regarding student beliefs about the nature of science:

> We see epistemology as part of one such domain – an intuitive theory of mind – that has a specific developmental history (e.g., Wellman, 1990). Understanding why junior high school students have these particular epistemological views consists of understanding their construction of a theory of mind, a process that begins in infancy. (p. 46)

It appears that the development of more sophisticated approaches to scientific activity and knowledge construction are both a product of and a driving force for the acquisition of knowledge within the epistemological domain. It seems likely that the processes by which students move through Piagetian levels of thought, through levels of understanding of the nature of science, and toward a more general understanding of the nature of knowledge are very similar. All involve the construction of new levels of understanding that are rooted in, but go beyond, the previous level. According to Moshman and Lukin (1989), the transcendence of each level is the product of recognizing that which was implicit in previous activity:

> In both domains [inductive and deductive reasoning], the stages embody a self-reflective trend in which the individual at each level reasons about (reflects on, "knows") the reasoning of the previous level. If we think of rationality as a self-

> reflective appeal to reasoning (Moshman & Hoover, 1989), the development of reasoning appears to move in the direction of greater rationality. (p. 188).

Carey (1985) made a similar claim regarding the development of formal operations:

> With respect to classes, for example, Inhelder and Piaget sometimes emphasize the child's developing ability to become conscious of the basis of their categorization. And certainly much of the work on formal operations was intended to be about metaconceptual development; e.g., although the young child clearly represents propositions, only in adolescence does the child become able to consciously scrutinize the proposition. In Piaget's writings, the distinction between metaconceptual change and format level change is not clearly drawn. (pp. 486-487)

According to Moshman and Lukin (1989), not all adults reach the metatheoretical awareness that characterizes the highest level in their categorization. This need not suggest that they could not reach this level if they were immersed in an atmosphere of authentic scientific activity and encouraged to reflect on the sources of their ideas. In fact, this is a growing trend in science teacher education (Baird, Fensham, Gunstone, & White, 1991; Duckworth, 1990, 1996; Dykstra, 1996; Fosnot, 1989, 1996; Gunstone & Northfield, 1994; Henriques, 1990; Julyan & Duckworth, 1996; Schifter, 1996). If teachers are to encourage the development of Level 4 FOI in their students, clearly it will be important for them to achieve the understandings that comprise this level.

### H.3. Focused vs. free exploration.

It is important to question the manner in which sustained focus on a guiding question is introduced as a goal for classroom inquiry. Although focus is undoubtedly important in generating deep understanding of a given topic, it is unclear at what point students should be challenged to develop the required metacognitive understandings that such activity requires. Should free-exploration be discouraged once students are able to engage in focused investigation at Level 3 FOI? Is a period of free-exploration required whenever a student undertakes an attempt to explain new or unfamiliar phenomena? What exactly is free-exploration? The answers to these questions are far from obvious, although for the purposes of this discussion, I will define free-exploration as activity that is uninhibited by the need to be related to an identified purpose: Within obvious limits defined by pragmatism, safety, and propriety, students are allowed to do what they wish with available materials. Such activity is necessarily based on some sort of purpose, but how this is defined is not mandated. The following discussion is divided into a consideration of the nature and role of foundational activity and a discussion of conscious diversions from an identified focus.

#### H.3.1. Foundational activity.

By the second day of investigating the vinegar and baking soda reaction, Robert and Samantha were already busy developing very detailed explanations regarding what might be happening to the tiny, unseen particles of the two substances. Keith was trying to determine the constituent parts of baking soda, water, and vinegar and trying to figure out more about the nature of and possible role of acids and bases in the reaction. Andrea had developed a less detailed, but certainly theory-based, explanation of the reaction as something being used up. These students did not seem to require time for free exploration of the materials. Did they partake in sufficient exploratory activity during the first day of class? They happily participated in filling balloons, popping corks from bottles, and extinguishing flames, and these activities did form a partial basis for their later explanations. Knowing how the materials behaved in different situations provided specific observations that could be accounted for in their explanations. However, gaining knowledge of components and properties of materials may be considered Level 3 FOI when the knowledge is gathered for that purpose. Here, perhaps, just about any investigation could be justified as grounds for understanding properties of the reactants and their interaction with both each other and other stimuli. However, to do so without any attempt to connect the ideas into a systematic whole would not transcend Level 2 FOI.

Certainly, all students have access to remembered experience that they routinely access as they attempt to generate and evaluate their ideas. Early in a discussion during which the class was trying to figure out why the direction of the battery is important in a walkman but not in a light bulb, Carl offered the following:

> Carl: At home, we used to have this fan, but I think it's broken now, and if you put the batteries in one way and turned it on, it had forward and reverse, but if you put the batteries in backwards, and if you turned it on to forward, it would go backwards. (Class Discussion, January 6)

This comment is not an articulate theory in response to the why question that was being considered, but it does portray an analogous situation that he seems to think might offer a helpful explanatory framework. But what prompted him to try the batteries in forward and reverse position in the first place? Did he just want to see what would happen? Was this part of a conscious attempt to determine whether direction was a salient factor in making the fan work? Was he trying to find out why you are supposed to insert batteries in a certain direction? To fully understand the role of focus, careful observation of the questions driving young children's undirected activity are needed. At this point, it is far from clear if different approaches to such activity are in fact evident.

Henriques (1990) strongly advocated extended periods of unguided activities during which children are permitted to interact with a collection of materials in any way they wish. After observing the activities of the children in these settings over an extended period of time, she generated and tested an interesting question:

> ...Why not start straight off with the proposed activities? Why not just use the spontaneous activity sessions as a field for observation and to make a list of activities for each grade level, and then propose these to pupils? The idea is tempting and much more acceptable and adapted to today's schools. We did in fact try this sort of procedure: We gave the same tasks and problems to children that had never been engaged in the spontaneous activity sessions. Of course we provided them with the same material as the experimental groups. The results were very significant. The work of the control group children – those who had not experienced the free activities – was very similar to the work that children of the same age showed during the first session of free activities. The children in the experimental group, on the other hand, took up the tasks we proposed with both seriousness and joy. Several of them even invented analogous tasks. It thus appears that for children at primary school level, interacting with objects is a deep intellectual and emotional need, and that the proposed activities are most meaningful when they follow the free activities. (pp. 176-177)

It seems that, given the opportunity to choose the manner in which they will interact with a set of materials, students select activity that is meaningful to them. This was evident in the work of the students at Level 2 FOI. A more extended observational period is needed to determine at what point, if any, these students would naturally attempt Level 3 FOI activities.

### H.3.2. Conscious diversions.

It is clear from examples of diversions during classroom discussion that they sometimes turn out to be very useful. Rachel's suggestion to heat vinegar prior to mixing it with baking soda led to quite a remarkable discussion that offered some important insights and posed some important questions regarding the nature of matter and its behavior in the presence of heat. These may have provided some of the students with a clearer mental model for thinking about matter that may then have benefited their understanding of the vinegar and baking soda reaction, but the ideas generated during the discussion were never related back to the focus question. Eager to take advantage of what seemed to be an excellent learning opportunity (on a related topic), I too, was guilty of a lack of focus here. Perhaps such opportunities would be more acceptable if they were recognized as diversions, thereby allowing a conscious re-focusing on the topic of investigation once the diversion has been explored:

Rachel: Uh, I just thought of another idea. A couple of years ago, we did warm water, and we stuck food coloring in it, and the food coloring spread more quickly than cold water. So, I was thinking of boiling vinegar and sticking baking soda in it and seeing what happens.

Matthew: We did that with hot water and salt. In cold water I know we put sugar in there and the hot water.... The sugar in there dissolved faster than it did in the cold water. We could see if there's a difference with hot water and baking soda in it.

Ms. S.: Why do you think it makes a difference?

Matthew: Well, probably the heat has something to do with it.

Ms. S.: What might the heat do to speed up dissolving or speed up the spread of color?

Keith: It melts it.

Ms. S.: What do you mean by "melts," Keith?

Keith: Like, you know, it dissolves it. It melts away in the liquid. So, in cold water, it dissolves. It doesn't get any heat. Like melting an ice cube.

Ms. S.: So, it breaks the particles apart more easily do you mean?

Keith: Yeah.

Ms. S.: Is that what you meant? Like, it breaks the ice away from the cube? Can you explain that a little more, Keith?

Keith: You know how water melts when you put heat on it?

Ms. S.: You know what? There's a few people that are playing in desks and stuff, and it will pick up [as noise in the video recording]. Can you remember to listen up to what Keith has to say? Then you can agree, disagree, give more examples, or whatever.

Keith: And in water, the ice cube melts slowly. So, if you put heat through it, it heats it up, and it melts it faster.

Samantha: Sort of like in the summertime. If you have an ice cube, and you're outside or something, and you.... Let's say you're outside in the middle of summer, and it's really hot out, and you take an ice cube and you put it in some pop or something. And you go outside, and you set it down and go play or whatever, and then you come back. Then the ice cube is, like, melted. But when you do that in the winter, the ice cube won't melt as fast, 'cause it's colder outside.

Rachel: Maybe, like in water or some of the stuff.... Maybe the particles or stuff like that are more active.

Ms. S.: In water than in...? More active than...?

Rachel: Like cold water or something. I don't know. Maybe!

Robert: Well, when an ice cube melts, it's still there.

Matthew: It's just in the water.

Jennifer: Yeah, 'cause you can taste it. It's all watered down then.

Matthew: And once you melt an ice cube, the water tastes different.

Andrea: This was a long time ago, but I had a bath, and I had this glass of water, and it had three or four ice cubes in it, and my bath water was really hot. And I just set the glass in the bath water, and the ice cubes melted really fast compared to when it's just on the table or something.

Ms. S.: Does that relate to what Rachel was saying, do you think? How might those connect?

Andrea: Well, it sort of relates to Samantha's. Like when it's hot outside and when it's cold.

Ms. S.: And, Rachel, how did you explain that?

Rachel: I was thinking of maybe, um, maybe the atoms are more active.

Ms. S.: When it's heated?

Rachel: Yeah.

Ms. S.: What do you guys think of this? I'm not hearing a lot of responses.

Samantha: When the water's cold, then it's more dense, and when the water's warm, it's less dense. Maybe since it's less dense, then it, like, has more room to move around, and when it's more dense, then they don't have enough, or that much, room to move around, so that might be why they're more active in the summer and not in the winter.

Robert: Still, the more dense one would weigh more.

Ms. S.: Why?

Robert: Because it's got more things in it.

Ms. S.: Does it, or are they just closer together?

Samantha: They're just closer together.

Robert: But if they're closer together, then there's not as much of it.

Ms. S.: So, if I take a marshmallow and scrunch it, it weighs more?

Robert: No.

Ms. S.: Well, they're more...closer together.

Robert: But then you need more marshmallows to make one

Ms. S.: So, you're talking about equal volumes?

Robert: Yeah, I guess so.

Ms. S.: Are we changing the volume, or are we just expanding it?

Robert: Expanding it.

Ms. S.: I mean.... If you had the same amount of cold water and the same amount of hot water, which should weigh more according to their theory? If you have the same volume?

Robert: Then they should weigh the same.

Ms. S.: If I had this much cold and this much hot, they should weigh the same?

Robert: No, the hot would weigh less.

Ms. S.: How come?

Robert: Because it's less dense. There's not.... It's spread out more.

Ms. S.: But if I took the same sample of water and heated it up, would it change weight as it got hotter?

Robert: Yes, because you're losing steam.

Ms. S.: Okay. We didn't heat it that much. We didn't heat it enough to steam it. It's just spreading out, but is it weighing any less?

Robert: No.

Ms. S.: Okay.

Rachel: I was noticing that when it's cold, they're more crowded together. Well, like, if you're crowded, you can't.... Like, if there's a whole bunch of people, you can't move that fast.

Robert: They would be warm. If you hook somebody, and you're close together, well then you're warm. But if you're away from them, well then you're cold.

Ms. S.: So how might all of this relate back to our vinegar and baking soda?

Robert: Maybe when...

Samantha: If vinegar's hot or if vinegar's cold, it will react different.(Class Discussion, May 15)

In a similar manner, during the electricity unit, Rachel connected a 6-volt battery in series with a weakened C-cell, partly to see if it would work, and partly to compensate for the low voltage from the other cell. This led to the observation that the C-cell was recharged by this process, and reasons for this were briefly considered prior to the group re-focusing on their task. This type of information could have provided valuable evidence for or against certain battery models later in the unit. Perhaps this awareness of diversion and the manner in which it allows conscious re-focusing are the keys to maximizing productive activity without losing valuable ideas that have no express relationship to the topic of inquiry. This leaves the amount of diversion as a judgement call, but one that can only be made when an understanding of focus is present. Samantha explicitly makes just such a judgement call in her individual battery interview:

> Samantha: So, it doesn't work, 'cause the battery's not dead after the first try. That's a new battery, and it didn't work. So if you have lots of these little guys, then maybe it takes one, and then it goes through here, and they go constantly, and you unhook it, then they go again.
>
> Ms. S.: What are you thinking?
>
> Samantha: I don't know.
>
> Ms. S.: Oh! You just got quiet for a minute.
>
> Samantha: I'm kind of thinking about a rechargeable battery. How I could make it up. But I want to finish this idea first. If you take all these and they go out, like make one go and then another starts here or something, then it should flash if one goes and then there's nothing and then another goes.... It should flash, right? (Battery Interview, March 30)

It seems that a balance between allowing the mind to wander and reigning it back in are once again critical considerations: Rational constraint on divergent thought remains an apt description of productive scientific thought.

### H.4. Clearly articulated, theory-based, and off-topic.

In some cases, the students observed in this study were able to articulate what it was they were trying to find out and what they expected to happen in a way that made the variable being tested internal to an investigation that was not centered on the guiding question. At first glance, this may seem to indicate a more advanced approach to investigation, but nonetheless diverges from the focus question and is therefore classified as Level 2 FOI. It could be argued that defining the guiding question limits the students and biases interpretations of their approach to activity in that context. However, the very general nature of the questions allowed highly divergent solution attempts, and the questions themselves grew out of larger discussions that involved each member of the class. In the cases that follow, what is even more telling is that even with self-selected questions, a sustained focus was typically not maintained, and often, results were not related to what appeared to be a new guiding theory. In several cases, explanations were generated after the experiment was in progress to satisfy my questions regarding the intent and implications of the investigations. The apparent theory-base of these investigations was actually a hindsighted justification for a WWHI investigation. It is also possible that the value of theoretically grounded investigation is apparent in certain contexts which are familiar to the students but that an abstracted understanding of the importance of theory in driving investigation is not. If so, situations where students spontaneously use the more advanced-level strategy may be fertile ground for reflective abstraction.

The piecemeal nature of Jordan's activities makes evident that he does not systematically base his investigations on theory. During the first few sessions, he conducted a variety of very interesting tests, which he summarized in his journal as follows:

> the viniger and Backing soda reminds of the proxid [peroxide] when it is on my finger. I found that when we put pH paper in a little viniger it would come out as a little acid then when I tried a lot it was a bright red and that means that it's would Be a large amound of acid. I trid to yons [use]the viniger from the yonst [?] and disolved Backing soda and the vinager was no good and did not work. I also found that viniger dose not mack elextristy but it conducts elextristy. I also found that it is like a battry because when it is put to in one it woukb but when I put one in one and another one in another one and Didn't work [when he put the probes of an ohmmeter in separate trays of vinegar, he didn't get a reading, but when he put both in the same tray, he did]. (Journal, April 20)

As Jordan was doing his pH tests, he commented that when you mix the vinegar and the baking soda, the pH paper turns yellow, but indicated that he didn't know what that meant. He went on to note that the vinegar "dissolves" the baking soda, which uses up all of the energy in the vinegar so that if you use it again, it won't work (which he tested). His test regarding whether used vinegar would work was based on this theory. This demonstrates one of few situations in which one of his investigations was clearly focused on a guiding question. He did not pursue this idea in greater depth to determine what might actually be happening to make the vinegar lose its energy.

Jordan's investigations with the ohmmeter appear to be based on a belief that energy in vinegar might register a voltage on a multi-tester (which he thought was a voltmeter). Given his knowledge base, this seems to be a reasonable inference, and it is relevant to the focus question. He claimed that when the probes of the tester were in the same tray, they generated a current, but that when they were in separate trays, they did not. He became quite excited by the results of this test, seemingly because of his realization that it was "like a battery!" (Field Notes, April 2): The positive and negative probes of the tester had to be in the same tray of vinegar for current to flow, just as connections to a battery have to occur from the positive to the negative terminal of the same battery (i.e. you can't light a bulb by connecting it to the positive terminal of one battery and the negative terminal of another). The apparent current was due to the fact that Jordan had the tester set as an ohmmeter rather than a voltmeter, so I explained the difference between the two measures to him. I wasn't sure if he understood what I was saying, but when he shared his finding with the class, he explained: "This charger or whatever it's called, a tester, is going to make its own energy, and when you put two in the same one, it creates energy, but when you put it in one or the other, it doesn't" (Class Discussion, April 20). Continued investigations regarding how the vinegar was like and unlike a battery occupied a considerable portion of the class discussion during which Jordan shared his results. Although the diversion was instructive and allowed meaningful connections to the students' understandings of batteries, Jordan did not refocus on the problem of vinegar losing energy. When he shared his results with the class, he focused exclusively on the battery-vinegar connection, and seemed to completely forget his original intent to determine whether vinegar had energy that could be measured. Robert's mention of power reminded Jordan of the results he wanted to share:

> Robert: [at front of room] See, first of all the baking soda - you saw it - Jennifer had it, and it was all hard and everything here. So now she put new vinegar in it, so now the baking soda has started a new war, and now the vinegar is winning, because it's on top, and it's got all the power. But now after awhile, then the baking soda will use all the vinegar, or all the vinegar will dry up, and then the baking soda will be the power, or have the power.
>
> Jordan: Hey! Power! I have something for that too, with the charger, or, that, uh, tester.

When Jordan demonstrated his findings to the class, the investigation was extended in a manner that had nothing to do with energy that might exist within vinegar:

> Jordan: Yeah, it goes through [a piece of string soaked in vinegar]! Not as much, but it still goes through.
>
> Ms. S.: It went through the string, Jordan?
>
> Jordan: Yeah. And then we're going to try it with wire now.
>
> Keith: It doesn't even bend.
>
> Robert: Just a second. It'll probably travel through the wire easier.
>
> Andrea: Well then why don't you try, like, if you can get, um.... If there's metal things like that, and try it with metal, like vinegar - vinegar, and then -
>
> Keith: That's what wire is.

In this context, Jordan maintained a sustained investigation for longer than usual, but again, one that was tangential to the vinegar and baking soda reaction. Even in this context he did not seek deeper levels of understanding once the questions that seemed to come naturally to mind were exhausted, and he quickly moved on to other things.

Over the course of the remaining class periods, Jordan conducted a wide variety of tests, often jumping from one to another without completing what he had started. First, he decided that he wanted to know if heating the vinegar and baking soda mixture would make a difference to the reaction. When I asked why he wanted to know, he said that it might be different after you heated it, because more of the substance in the vinegar could be dissolved. He did not develop a way of measuring whether in fact the reaction would be different and did not report the results of this test. It is unclear whether he had considered this explanation prior to my questioning. Again, although his test now at least appeared grounded in theory, neither the confirmation nor the rejection of his hypothesis would deepen his understanding of the vinegar and baking soda reaction.

Following the heat test, Jordan decided to investigate the following question: "Why when you let it dry it is hard as rock and rough then when you put new viniger in it it gets soft and starts to smothen? Then when you put backing soda it smothens totally?" (Journal, May 4). He also wrote down a theory: "What Think happens is the gas always is getting made and it hardens when it is rising and causes the rough surfece." Although he verbalized a theory, the tests he subsequently conducted were not useful in for evaluating it and essentially consisted of repeatedly mixing vinegar and baking soda and drawing pictures of the results. His attention was apparently focused on whether the mixture would keep getting hard, which he had already observed.

After this he watched pH paper under the microscope as it changed color and watched Frank test whether he was making carbon dioxide gas. The next day, he mixed baking soda and vinegar in a petri dish, claiming to be re-testing one of Jennifer's investigations, because he didn't know if hers was fair.

The following day, Jordan set out to repeat Rebecca's test comparing the effect of distilled water vs. normal water on the vinegar and baking soda reaction by using limewater as an indicator for how much gas formed. Before completing this test, he decided to make crystals of vinegar, baking soda, and mixed-vinegar-and-baking-soda crystals. This was the result of his becoming interested in a procedure he had read about that told how to use a cotton string to grow them. Although he did set up dissolved solutions with strings, he used his solutions for another test before the crystals had a chance to grow. When he returned to the test comparing distilled and normal water, he indicated that he could tell how much gas was produced by how dark the limewater turned and by how far the foam went across a tube connecting the flask with the limewater and the flask with the vinegar and baking soda. His purpose in conducting both the crystal and the limewater test appeared to be an interest in the apparatuses used to conduct them.

Jordan's final test involved a comparison of the effects of mixing a variety of ENO, TUMS, sugar, salt, and water combinations. For the final series of tests, he was able to develop connections with the vinegar and baking soda reaction, but only in response to extensive questioning after he had completed the test. As is evident in the following discussion, doing so was not part of his initial motivation in mixing these ingredients:

Jordan: Uh, what I'm doing is, uh, the same as last time, but now I'm wanting to know what sugar does with baking soda and vinegar.

Ms. S.: What sugar does?

Jordan: Yeah.

Ms. S.: Okay. And how come?

Jordan: I don't know.

Ms. S.: What will that tell you?

Jordan: Just if sugar makes a difference. Like, the crystals, if they're different than the baking soda and vinegar one.

Ms. S.: Okay. Sure. And are you going to look at them before and then look at them after?

Jordan: Yeah.

Ms. S.: Which crystals are you looking at before, then?

Jordan: Uh, the baking soda and vinegar.

Ms. S.: How about sugar?

Jordan: And sugar.

Ms. S.: And then you'll look at them again afterwards?

Jordan: Yeah.

Ms. S.: And then you'll know if.... And what will that tell you?

Jordan: Uh....

Ms. S.: What is it that you want to see as you look at all of that? What are you trying to find out?

Jordan: To see if it makes a difference with the baking soda and vinegar crystals.

Ms. S.: Okay. Questions or ideas for Jordan?

Carl: Why do you want to test sugar? Like, I don't think it has anything that will react with vinegar.

Jordan: How do you know?

Carl: I don't, but -

Keith: What is in sugar?

Robert: Yeah.

Carl: Glucose for sure. (Class Discussion, May 25)

Two of Rebecca's tests also clearly fit the description of well-defined, but unclearly focused investigations. She developed quite a detailed explanation of the vinegar and baking soda reaction that described rearranging particles, and went on to test the effect of new vs. used ingredients on the reaction. However, she abandoned this line of reasoning to test the effect of normal vs. distilled water. She was extremely careful to control necessary variables and took painstaking efforts to obtain accurate measurements. However, she did not consider either the rationale for such a test or the implications of its results.

Following the water test, she compared the effects of different types of salt on the resulting crystals, because she thought that they might somehow affect the reaction. This time, she did provide a relatively articulate rationale for conducting tests involving vinegar, baking soda, and either coarse or table salt: "I think that different salts will affect the fiz [fizz] and gas because it might add more ingrents [ingredients] and other adoms [atoms] might exapt [escape] and turn it into another gas" (Journal, June 3). However, she did not articulate an understanding about how finding out that salts produce a different gas or a different crystal would impact her understanding of the vinegar and baking soda reaction. She partially answered her own question by identifying the gas produced during the vinegar and baking soda reaction to which coarse salt had been added as carbon dioxide, but there is no evidence of an effort to explain why the gas did not change as she had predicted.

### H.5. Technology-based activity.

Although technology-based activity was observed infrequently, there were instances in which the students set clearly defined goals and tried to achieve them. Such goals involved the invention of a tangible product or the generation of an effect that was identified prior to engaging in the activity. In such cases, troubleshooting takes the place of asking, "Why?", although causal explanations may be sought when they are expedient to the troubleshooting process. Attempts to see how brightly one is able to light a bulb or how far one is able to shoot a cork from a bottle containing vinegar and baking soda are typical of this type of activity. For the most part, such activity was engaged in only during brief excursions from the main point of investigation or as a means of developing more efficient apparatuses or workspaces. The invention of mini-flashlights or mini-wall lights while the students were working on the dark stage is one such example.

In applying a blanket Level 2 FOI classification to technology-based activity, I am neither attempting to dismiss the value of all such activity nor suggesting that technology-based activity is all alike. Undoubtedly, developmental levels to describe student approaches to technologically oriented goals could be developed as well. Perhaps students who demonstrate this sort of motivation would make excellent engineers. Their ability to focus on the pragmatic aspects of a task without being distracted by the need to develop causal understanding of phenomena that could be unnecessary to the development of a functional product may be beneficial in a technological context. This difference is likely one of emphasis rather than of kind in that understanding plays an important role in the design process. An example serves to illustrate the point: As the students were attempting to figure out ways to set up various circuits in the context of a problem regarding how to make their burglar alarms go off in several rooms at once (a technological goal), one of the students asked whether it would matter which way the bulb was connected to the circuit. She tested a bulb and found that it made no difference. For all practical purposes, the investigation could have ended there. However, the students then launched a rather lengthy discussion regarding why direction of the batteries matters in some flashlights and in Andrea's walkman, but does not matter in other flashlights or in the small bulbs they had been using in their circuits. My purpose in posing the wiring problem was actually to generate discussion regarding different types of circuits, and I encouraged their digression. However, in terms of focus on a guiding question, we should have concentrated our efforts on achieving the goal of developing effective burglar alarms. Although there would likely be overlap, a study designed to investigate how children design and troubleshoot prototype devices and techniques might result in very different emphases regarding the types of questions that are valued. For the purposes of science inquiry, the current emphasis is appropriate.

# APPENDIX I

## The Role of Reduction

### I.1. The role of reduction.

> *As stated before, I have spent a professional lifetime compiling statistical data of this sort for the growth of organisms and the evolution of lineages. I have a sense of the patterns expected from such data, and have learned to pay special attention to noise and inevitable departures from expectations. I am just not used to the exceptionless data produced over and over again by the history of baseball. I would have thought that any human institution must be more sensitive than natural systems to the vagaries of accident and history, and that baseball would therefore yield more exceptions and a fuzzier signal (if any at all).... Again, I get the eerie feeling that I must be calculating something quite general about the nature of systems, and not just compiling the individualized numbers of a particular idiosyncratic institution.*
>
> (Gould, 1996, p. 122)

The following discussion is somewhat speculative but raises important questions regarding the nature of knowledge structuring. It focuses on the possibility that developing an understanding of the importance of reduction may lead to more efficient knowledge structuring that better facilitates analogical reasoning.

It appears that the reduction of knowledge to levels at which relational structures are identical may be importnat in driving the analogy-generation process. This is particularly applicable in terms of analogies generated "from a broader principle" (Clement, 1981, p. 139). Although analogs identified by means of the direct association of an individual component of source and target phenomena are also important, salient likenesses are less likely to be recognized in the specifics of phenomena than they are in more general frameworks. This may be compared to biological classification: It is easier to classify a new organism as a member of a particular phylum than it is to classify it as a member of a specific species. The more specific the criteria that have to be matched, the fewer the number of phenomena that are likely to match, but the more likely it will be that explanatory structure may be appropriately transferred. The reverse is also true: The more general the criteria to be matched, the greater the likelihood that there will be matching phenomena, but the less likely it will be that those phenomena will share causal relations. Generative transformations are another important source of analogies, but are typically created in response to the identification of non-corresponding elements in analogs generated by one of the other methods.

I view analogical relations as common points in the web of ideas that is the human mind. For example, when Carl associated the vinegar and baking soda reaction with a burning log, the two were likely connected by a broader principle, such as the nature of escaping gas, that allowed him to recognize them as similar. For this to happen, both the fire and the vinegar and baking soda reaction had to be stored in Carl's mind in a reduced form that was identical at some level of abstraction. Perhaps he viewed the burning log via a simplified mental image of escaping particles or even a more detailed visual image of reacting particles (he seems to have a fairly advanced view of the particulate nature of matter). As he thought about the vinegar and baking soda reaction, he may have reduced it in a manner that directed his conscious thought to that very point in his mind. This point may be envisioned as a nodal point that is also connected to the burning log situation.

Mapping shared features between analogies identified through common details in the manner in which they are represented within the mind could facilitate the development of this type of reduction. The reduction itself is the set of shared components and relations that exist between two or more phenomena. Because they are more general than the specific details that prompted their identification, they become more widely applicable in this form. This may be an important element in the formation of integrated knowledge structures that facilitate the identification of analogies that are based on shared broad structure.

If this view is accurate, the reduction of complex events or processes emerges as a critical feature in the creation of mental structures that would facilitate the development of integrated knowledge structures. It would seem that diverse experiences that are reduced to order would create a mental web with a broad range of intricately connected explanatory structures that would facilitate the identification of the outwardly diverse analogies that are so often seen as a hallmark of creativity and a mark of scientific genius. When only particulars are connected, they are less likely to reveal similarity with transferable explanatory structure.

This view begs several questions: Are students who demonstrate tendencies to reduce their ideas to abstractions more likely to generate analogies, or more likely to generate analogies that go beyond surface similarities? What prompts the mind to engage in reductive processes? Can reductions plausibly explain the analogies that students develop? Both Carl and Samantha tended to reduce their ideas, and both articulated many analogies throughout both the electricity and chemistry units. Is this typical? Is there a causal relationship between these factors? If so, in what direction(s) does it act? In Carl's case, the tendency to reduce his ideas sometimes led to difficulty in that he reduced them to a point at which he no longer considered the specific features comprising the reductions and was therefore unable to evaluate effectively the analogies that he based upon them.

As with analogy, reducing ideas to higher and higher levels of abstraction seems to be part of the natural functioning of our minds. However, some students do this to a much greater extent than others. One area in which this is exemplified is in the tendency of some students to explain phenomena with one or more examples, whereas others seek out the commonalties between those examples to create more generalized descriptions or explanations of the phenomena or processes in question. There is little evidence to suggest that this is the result of a conscious effort, however. Understanding the role of reduction may occur at the level of metatheory after it has been subconsciously in effect in familiar domains. But what drives reduction in familiar domains? The need to deal with large amounts of information may motivate the process, whereas the ability to map analogs may at least help to facilitate it.

As explanations become increasingly complex, it becomes difficult to keep all of the arguments and images in mind at a single time. As certain pieces of an explanation or mental model become familiar, they may be chunked to facilitate processing within short-term memory. It is unclear whether this may be done consciously or if doing so is always beneficial, but it is clear that some students do this very proficiently while others remain mired in detail in a way that makes it difficult for them to view an explanation in its entirety or to identify a broader structure that could be transferable to other situations. This may explain apparent inconsistencies in some students' reasoning: If a student is unable to reduce collections of information in a manner that allows that information to be dealt with simultaneously in short-term memory, inconsistencies cannot be made apparent. This has clear connections to isolated-case reasoning, which is dealt with in Section 4.3.3.1.

Identifying the positive aspects of analogs forms a generalized structure common to source and target analogs. This generalized structure is a reduction or abstraction. Here, the difference between Level 2 and Level 3 AR becomes critical: If only the features which drove the identification of the analog in the first place (through individual features or through broad structure) are taken into account, the reduction remains general and may appear to constitute a collection of examples and counter-examples. The unexplained phenomena may be explained as like *a*, *b*, or *c* or unlike *d* and *e*, whereas the specifics of commonality remain unclear. If, through Level 3 AR validation strategies, questions such as, "How else are they alike?", "How are they different?", "Do the similarities occur for the same reasons?", or "Why is it a member of that category?" are posed, the reduction becomes more explicit and specific, and may constitute a more clearly focused general explanation that attempts to define what *is* rather than simply identifying other situations which are like and unlike the one being explained.

It appears that analogy and reduction may be mutually reinforcing. Although conclusive evidence is unavailable, facility with mapping and evaluating analogies may be a key to developing the reductions that comprise integrated knowledge structures and which may then contribute to the identification of further analogs. I would also tentatively speculate that understanding analogical may be a catalyst or starting point for this positive-feedback loop, and that it may be a more productive arena for student reflection than reduction per se. However, it is possible that the importance of reduction could become apparent at higher levels of metatheoretical reflection.