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Seeds of Science Practice: Parallels Between the Science Thinking and Activities of Sixth-Grade Children and Professional Scientists

by

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Abstract

In the dissertation it is argued that the practices of children engaged in science inquiry share important — but often overlooked — characteristics with professional scientists. These practices are referred to as "seeds of science practice" because they have the potential, as they develop, to support increasingly rich science exploration.

Data was collected during six months of research in a sixth-grade classroom. Themes from the history, philosophy and sociology of science that are used as tools for analysis include: science in the making, the role of background influences, and the identification of contradictions. "Seeds of science practice" are identified in three important science activities: the generation of questions, defining the terms central to a science investigation, and the creation and interpretation of models. The analyses of episodes from the history of science and learning stories from the classroom reveal similarities and differences between the children's science practice and that of professional scientists.

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Chapter 1: Introduction

This dissertation is an investigation of the thinking and learning of a group of sixth grade children engaged in science inquiry. Its goal is to identify the strengths of the children's inquiry process. The thesis of the dissertation is that the thinking and activities of children engaged in science inquiry share important — but often overlooked — characteristics with the practice of professional scientists.[1] The children's practices have the potential, as they develop, to support increasingly rich science exploration; they will therefore be referred to as "seeds of science practice."[2] The identification of these seeds of science practice is the central goal of this dissertation. Themes from the history, philosophy and sociology of science are used as tools for analysis.[3] Among the most important of these for the dissertation are: science in the making, the role of background influences as interpretive frameworks, the identification of contradictions and other challenges to ideas, and the value of using groups as units of analysis.

These themes are used to interpret data collected during six months of research in a progressive sixth-grade classroom, where I took on the diverse roles of observer, participant, interviewer, and activity leader. I identify seeds of science practice in three important science activities: the generation of questions that can initiate science exploration, defining the terms central to a science investigation, and the creation and interpretation of models. Each of these will be analyzed in one of the core chapters of the dissertation.

Using episodes from the history of science I highlight and elaborate on the themes and detail the processes and challenges that are part of the activities central to each chapter.

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[1] In referring to science practice, I do not claim that there is a single, normative epistemology of science, that science is unique, that differences between sciences are not significant, or that professional science practice should be the goal of all children.

[2] As will be addressed later in the chapter, the concept "seeds of science practice" derives from Hammer (1995).

[3] At times, for purposes of conciseness the phrase, "studies of science," will be used to refer collectively to history, philosophy, and sociology of science.

The resulting ideas support the analysis of "learning stories" (Papert, 1992) about the sixth graders' science explorations.

The next sections elaborate on the four themes from the studies of science that are tools used to analyze the thinking and activities of scientists and children: "science in the making," background influences, contradictions, and the group as a unit of analysis.

Science in the Making and Ready-Made Science

The Relationship between Science in the Making and Ready-Made Science

In this dissertation I use the concepts, *science in the making* and *ready-made science*, to help uncover the seeds of science practice in the thinking and activities of children engaged in science inquiry. These concepts are taken from Latour (1987) and distinguish science that is still in the process of construction from science that has become established.[4]

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[4]In this dissertation I make use of the concepts of ready-made science, and science in the making. However, I do not share all of Latour's views about science. The importance of social construction in the practice of science is incorporated into my analysis, but in contrast to Latour, I also assume that "nature" is a significant source of constraint on the success of such constructions. For a like-minded critique of these issues from the perspective of a sociologist of science see Cole (1992). Stephen J. Gould expresses (1981) a similar point of view:

> Science, since people must do it, is a socially embedded activity. It progresses by hunch, vision, and intuition. Much of its change through time does not record a closer approach to absolute truth, but the alteration of cultural contexts that influence it so strongly. Facts are not pure and unsullied bits of information; culture also influences what we see and how we see it. Theories, moreover, are not inexorable inductions from facts. The most creative theories are often imaginative visions imposed upon facts; the source of imagination is also strongly cultural.
>
> This argument, although still anathema to many practicing scientists, would, I think, be accepted by nearly every historian of science. In advancing it, however, I do not ally myself with an overextension now popular in some historical circles: the purely relativistic claim that scientific change only reflects the modification of social contexts, that truth is a meaningless notion outside cultural assumptions, and that science can therefore provide no enduring answers. As a practicing scientist, I share the credo of my colleagues: I believe that a factual reality exists and that science, though often in an obtuse and erratic manner, can learn about it. Galileo was not shown the instruments of torture in an abstract debate about lunar motion. He had threatened the Church's conventional argument for social and doctrinal stability: the static world order with planets circling about a central earth, priests subordinate to the Pope and serfs to their lord. But the Church soon made its peace with Galileo's cosmology. They had no choice; the earth really does revolve about the sun (Gould, 1981, pp. 21-22).

Ready-made science is science that has been accepted by the scientific community — the facts, techniques, artifacts and theories for which the rough edges have been smoothed out, and which can be considered "black boxes" by their users. What characterizes black boxes is that, "no matter how controversial their history, how complex their inner workings ... only their input and output count" (Latour, 1987, p. 3). For example, the double helix structure of DNA is a black box that molecular biologists now take for granted, although in the 1950's it was one of several competing models. In contrast, "science in the making" is science at the frontiers of knowledge, where phenomena of interest must be identified, important terms defined, and the validity of instruments justified.

These are interrelated parts of science, and both are important. Ready-made science supports science in the making, and *vice versa*. A scientist doing cutting edge work may find that the models and theories she is developing are in flux. In this way, she is involved in science in the making. At the same time, she is relying on products of ready-made science, such as particle accelerators, the rest mass of well known particles, and standard calculations that incorporate the special theory of relativity.

However, before the value and validity of ideas, instruments and techniques become established — i.e., part of the ready-made science on which scientists rely — they are part of science in the making. This status can affect the way in which a scientist's work is received. For example, when Galileo made many of his striking discoveries (such as the canals of Mars, the moons of Jupiter, and the phases of Venus), the optical telescope was a novel instrument that had not yet been accepted by the science community. Skeptics, therefore, argued that his observations were artifacts of the instrument and did not correspond to real world phenomena. Later, the telescope became an established tool of astronomy — i.e. a part of ready-made science — and the validity of Galileo's observations was no longer controversial.

As noted above, if a line of research is successful some of the new techniques and ideas it develops will become part of ready-made science, furthering the iterative cycle of exploration. However, many ideas do not make a successful transition from science in the making to ready-made science. For example, around the turn of the century Blondot used a special device to produce patterns he attributed to a new kind of energy, which by analogy to X-rays, he called N-rays. For several years, there was a flurry of N-ray research and publication around the world. Then a skeptical researcher, who had been unable to reproduce these findings, came to Blondot's laboratory to investigate his experimental techniques. He surreptitiously removed the prism that was supposed to produce the "N-rays" and found that they still persisted. Further research on N-rays soon halted and N-rays never became a part of ready-made science. A current example is that of cold fusion, which continues to have a small number of adherents despite the fact that it has been rejected by most of the scientific community.

Because of the potential controversy accompanying techniques that are part of science in the making, scientists may try to obtain their results using tools of ready-made science. For example, in applying his theory of gravitation to calculate the orbital period of the moon, Newton proved some of his important sub-results (such as the fact that the gravitational influence of a sphere of uniform density is the same as that of an equivalent point mass) using his own invention, the calculus. Because the calculus was not widely known he delayed publishing his foundation work, the *Principia Mathematica,* until he was able to obtain the same results by well-accepted geometric methods.

It is important to note that science in the making and ready-made science are not an absolute dichotomy. They should be viewed as tools for thinking about science and science learning. For example, looking at professional science in the making focuses our attention on the innovative aspects of the process of science that are essential to its growth. I use a focus on science in the making in order to help understand the children's science thinking and activities and to identify their strengths. At the same time, however, ready-made science is valuable because it provides the foundation on which science in the making is built. As children explore different topics and use and invent tools and techniques to support their explorations, therefore, it is helpful for them to gain access to relevant ready-made science. This includes explicit knowledge found in texts, as well as tacit knowledge that is often gained experientially and taken for granted by a community of practice. The importance of this tacit knowledge, which is often ignored in school science, will be highlighted in chapter 6, on the creation and interpretation of models.

The Relationship between Science in the Making and Children's Science Practice

Both science in the making and ready-made science are present in the learning stories. However, my analysis will emphasize science in the making. This is because children's strengths are better recognized by focusing on the abilities they bring to science explorations, and not on their knowledge of science content and technique. A focus on ready-made science highlights their incorrect conclusions, while a focus on science in the making draws our attention to the strength of their reasoning.

The focus on science in the making also helps highlight a weakness of traditional school science, which tends to emphasize ready-made science to the exclusion of science in the making. In addition to denying children an opportunity to put their potential science abilities to use, this focus gives them a misleading, and unappealing, view of science.

Background Influences

What Are Background Influences?

Accounting for the role of background influences is a second theme that I will frequently use to help understand the children's thinking and activities. These background influences include: everyday experience, beliefs common in the culture, and facts, ideas, and theories learned in more formal settings.[5]

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[5]The phrases "background influences" and "background experiences and beliefs" will be used interchangeably. Neither term is intended to fully characterize the nature of these influences.

The concept of background influences is derived from the history and philosophy of science, which emphasize the importance of understanding the work of historical scientists in terms of their own theoretical frameworks and the ideas of their surrounding cultures. For example, taking their background beliefs into consideration can give us greater insight into why the alchemists continued to repeat their experiments, despite a striking lack of success. As noted by Toulmin (1962), these beliefs included astrology and the influence of one's spiritual purity on experimental outcomes. Consequently they frequently attributed the failure of their experiments to the inauspicious position of the stars, or to a lack of spiritual purity, and therefore repeated them when conditions seemed more favorable.[6] By knowing about these beliefs we are better able to understand the rationale for the alchemists' persistence.[7]

Several kinds of background influences are addressed in the analysis of the learning stories, and are illustrated here with examples discussed in the dissertation. Children often make use of *experiences from daily life*, such as the feeling of tilting, smells familiar from eating and cooking, or the knowledge that video-cassettes enable one to transport recorded images from one location to another. They also *generalize from their experiences.* Drawing on their familiarity with dolls and model airplanes, for example, they may assume that models capture only appearances, and not inner workings. *Knowledge from reading, school, or other learning environments*, such as the role of olfactory neurons in smell or the contribution triangles make to the stability of structures, are also background beliefs that children bring to their science learning. Children may also use ideas that circulate in the

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[6]In addition to helping us understand the "failures" of historical scientists, such as their inability to meet their own research goals, knowledge of their background influences may also help us understand their successes. For example, the alchemists were concerned with the purity of the material substances they were using, and they developed glassware and techniques for distilling and isolating substances that made an enduring contribution to science.

[7]Understanding background influences enables us to make sense of historical investigations of physical phenomena. This does not imply that we must consider these investigations to be science. As will be pointed out below, lack of falsifiability is one reason to exclude the alchemists' work from the realm of science.

larger culture but which they have incompletely assimilated, such as the theory of evolution, or the "big bang" theory.

Because these experiences and beliefs serve as lenses through which people interpret situations, events and phenomena, they play a critical role in guiding one's scientific exploration. When these background influences are shared, they may become essentially invisible. However, when they differ, as is often the case when we are dealing with scientists from an earlier era or children, awareness of relevant background influences may be necessary to understand their thinking.

Shared background influences are usually taken for granted in everyday communication. For example, the statement "I dropped my cup, and gravity made it crash to the ground," would ordinarily be thought of as a description, not an *interpretation* of the cause of the cup's fall.[8] The theoretical concept *gravity* is a shared background influence. The speaker and listener might not hold precisely the same concept, but would agree that gravity "makes things fall down."

However, if the speaker and listener do not share the same background influences, the speaker's words may not make sense. For example, someone holding the world view of Aristotelian physics would say that the cup was "seeking its natural place," an idea that would not be meaningful to an ordinary person today, who would consider gravity a force. At the same time, this ordinary person might make a statement about force that does not make sense in terms of Newtonian physics such as, "I gave the stone an upward force by throwing it. As that force died out, it became less than the force of gravity and the stone began to fall." This statement can be understood in terms of concepts such as "impetus," which were held by earlier scientists and which derive in part from experiences in a friction-filled world (Clement, 1983; diSessa, 1982; McCloskey & Kargon, 1988).

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[8]The following real-life example illustrates a rather different interpretation of a similar event. Hearing a crash in the next room, a mother rushed in and found her daughter standing over a shattered cup. "I'm so lucky" the girl said, "I let go of the cup (just) before it broke." (C. Krug, personal communication.)

In short, people's ideas and experiences serve as lenses through which phenomena are interpreted. To the extent that these background influences differ from our own, the actions and thinking of others will be more difficult to interpret.

Why Background Influences Are Important in the Dissertation

In the dissertation, two main uses are made of the concept of background influences. First, consideration of background influences is used to make sense of the activities and thinking of the children. Second, taking note of how they use background influences to make sense of the world and generate hypotheses allows us to identify similarities between children and scientists that might otherwise pass unnoticed.

The experiments of the alchemists provide an example of how understanding background influences enables us to make sense of what might initially seem an entirely unscientific endeavor. Similarly, consideration of the background influences affecting children's thinking and activities can help us see that even when their conclusions are scientifically incorrect, children may be engaged in good thinking that we fail to recognize. For example, when children claim that the seasons are caused by the earth's changing distance from the sun, they may be bringing in two pieces of background knowledge. From their everyday experience with heat and temperature they know that the closer we stand to a stove or fire, the hotter we feel. In addition, pictures in books may have given them the incorrect idea that the earth's orbit is highly elliptical (although it is, in fact, nearly circular). Taking these background beliefs into consideration enables us to recognize the plausibility of their conclusion despite its inaccuracy.

Background influences will be used throughout the thesis to highlight similarities between children and scientists. For example, learning stories in the chapter on questions and contradictions will show that children, like scientists, are able to recognize contradictions in situations that are unproblematic to their peers. Background influences can also help us identify differences between children and scientists. This point emerges in the chapter on models, which discusses the way in which a girl's familiarity with models that capture only the appearance of phenomena (a background influence) prevents her from understanding a model with potential explanatory value. These examples show how consideration of background influences can help us identify the seeds of science practice in children's explorations.

Contradictions

The third theme used to highlight similarities between children and professional scientists is the role of contradictions in generating, driving, and sustaining scientists' and children's investigations. The analyses will show that just as contradictions play an important role in professional science practice, they can play an important role for children exploring in an inquiry science environment.[9]

Why Contradictions Are Important in Philosophy of Science

For at least the last half century, philosophers of science have emphasized the key role of contradictions in science. Karl Popper (1959) was, perhaps, the first to stress the importance of conjectures and refutations. In contrast to the logical positivists of the early 20th century, who sought to "prove" scientific theories by reducing them to statements about sense data, he argued that scientific theories could not, by their nature, be proven. For him, the essence of science was falsifiability. For a theory to be "scientific" there must be hypothetical circumstances (e.g., experimental results) under which the theory could be shown to be incorrect. For example, by Popper's criterion, alchemy would not be considered a science because its practitioners could justify all unsuccessful results by

[9]The term "contradictions" is used in this dissertation to stand for a variety of challenges to claims and ideas in science. In particular, it should be noted that these challenges may not reveal a problem in the idea challenged. For example, the difficulty may lie in the challenger's own background influences, an inaccurate observation, or relevant information not known by either or both of the involved parties. Therefore although the term "contradictions" incorporates this possibility, the phrase "perceived contradictions" will sometimes be used to emphasize it. Similarly, "contradictions" will be used to incorporate other challenges such as inadequacies, counterexamples, and counterarguments. Briefly, the meaning of these terms is as follows. Inadequacies are ways that a theory or idea falls short in accounting for a phenomenon, or ways in which an explanation seems forced or implausible. A counterexample is a specific instance or phenomenon that (allegedly) shows a failure of a claim. A counterargument is an argument offered against a claim. The use of a counterexample, or a demonstration of an error in the logic of an argument are two kinds of counterarguments.

appealing to inauspicious astrological conditions, which could not be specified in advance, or insufficient spiritual purity, which could not be objectively measured.

If a contradiction between a theory and empirical data is deemed important and cannot be overcome (e.g. by altering a non-crucial aspect of the theory, or accounting for the contradiction in another way) then the theory will become falsified, as happened with N-rays.[10] Thus, contradictions serve a feedback purpose. They provide a motivation and goal for improving a theory. Furthermore, they provide a challenge that may reveal the limitations of a theory.[11]

An example of a contradiction that was acknowledged but tolerated was that between the measured rate of precession of the perihelion of Mercury and the prediction made by Newtonian theory. Although this was problematic, it was not considered significant enough to falsify Newtonian theory, which was enormously successful in accounting for astronomical and terrestrial phenomena. The physics community recognized it as an anomaly, which they fully expected to be resolved.[12]

Lakatos (1970) introduced a number of concepts that echoed Popper's stress on the significance of falsifiability, but which he believed corresponded more closely to the actual practice of scientists. He noted that for most scientists the goal of experimentation is confirmation, not falsification, of their work. In his view, the source of contradiction in science practice comes from proponents of rival theories, who, in conducting experiments to support their own theories, also challenge the theories of their colleagues. Furthermore, in analyzing the impact of contradictions on a "research programme" he distinguished between its "hard" core of essential beliefs, which cannot be changed without destroying its integrity, and a "soft" core of beliefs that can be altered if necessary to protect the hard

[10] It should be noted that the question of whether a specific challenge actually falsifies a theory is often controversial.

[11] Those holding a "realist" view of science, which includes most practicing scientists, would see this feedback as reflecting how well the theory matches "reality." Social constructionists would emphasize the role of interactions between scientists and others, in what Latour (1987, p. 74) calls "trials of strength."

[12] One unsuccessful attempt to do so involved the gravitational effect of a hypothesized small planet orbiting closer to the sun than Mercury. The general theory of relativity eventually resolved this anomaly.

core. He also offered a standard for judging the success of a research programme. It can be progressive — continuing to productively solve new problems, or degenerating — increasingly unable to meet the challenges created by new experimental and theoretical discoveries. Thus, a particular contradiction might not cause a theory to be considered falsified, but could lead it to be perceived as degenerating and to a loss of adherents.

Philosophers of science, therefore, have emphasized the importance of identifying contradictions in order to eliminate inadequate theories and to increase our confidence in those that survive. When we turn from philosophy of science to historical examples of science practice, we also find that contradictions are, in fact, essential to the progress of science. This will be illustrated in the discussion of historical questions involving contradictions in chapter 4.

Children and Contradictions

Contradictions play a similar role in the science practice of children and professional scientists. Both groups have a well developed ability to identify contradictions. Once identified, these contradictions may stimulate further development of an idea and strengthen it, or challenge the idea, so that it is weakened or abandoned. Examples in the questions chapter will highlight the children's ability to identify contradictions. In the chapter on constructing definitions, the role of contradictions in stimulating debate will be illustrated as the children argue about intelligence and whether or not nighttime is a shadow.

An important difference between children and professional scientists is that children tend to identify contradictions much more readily in the thinking of others than in their own. Scientists, in contrast, are practiced at applying critical skills to their own ideas, as well as those of others. Furthermore, although most children are highly motivated to find flaws in the ideas of others, professional scientists put most of their time and energy into building and defending their own theories. Another difference is that arguments in science take place over a longer time period than children's typically do. In addition, while the children's arguments took place primarily in the context of face to face interactions, debates in science are frequently carried out in written media such as journals.

Children's ability to identify contradictions will be illustrated in chapter 4, on questions. In that chapter, the contribution of contradictions to the dynamics of exploration will be analyzed in learning stories about children's attempts to define the terms "shadows" and "intelligence."

Groups and Shared Beliefs and Practices

The Role of the Group

The role of the group is another theme used to analyze children's science thinking and locate the seeds of their science practice. This theme builds on the emphasis placed by historians and philosophers of science on groups and their shared ideas, practices, and tools as units of analysis. These considerations are applied to the children's science explorations to show ways that their group practice is like that of scientists, as well as to identify differences between children and professional scientists. Additionally, it is argued that at times children as a group may function more like an individual scientist than as a group of scientists.

How the Studies of Science View Groups

In his introduction to *The Structure of Scientific Revolutions* Kuhn (1970) highlights the difference between recent approaches to the study of historical science and the approaches that were dominant earlier. Earlier historians of science viewed the progress of science as incremental. Therefore, they focused on identifying and studying the first individuals to achieve important scientific milestones, as well as the barriers that caused others to go astray. However, modern historians of science attempt to understand the efforts of previous scientists in terms of the ideas and practices of their era. Kuhn (1970) introduced the concept of a *paradigm* to refer to the beliefs and practices shared by a group of scientists. These include ontological commitments, the criteria for valid explanations, and the agreed upon set of tools and methods for conducting experiments. Thus this theme concerns groups of individuals, as well as their collective ideas and tools.

Although philosophers of science have criticized some aspects of Kuhn's analysis, they agree on the importance of communities of research and on the relevance of shared ideas and practices to progress in science. They conceptualize them differently, however. For example, Lakatos' (1970) concept of research programmes with a research agenda, and hard and soft cores is somewhat analogous to Kuhn's paradigms. Lakatos does not make Kuhn's distinction between normal and revolutionary science, but does distinguish between whether a research programme is "progressive" or "degenerating." Thus, they both discuss modes of scientific progress in terms of collectives, not individuals.

The importance of communities for sustaining research is illustrated by Toulmin and Goodfield (1961) in their analysis of the decline of Greek science from 300 B.C.E. to 200 C.E. During the fifth and fourth century B.C.E., the center of Greek science was the schools and academies of Athens. Athens lost its centrality after it was conquered by Alexander the Great, who set up a new center for science in Alexandria. Other centers of science arose in Syracuse and Rhodes. However, as scholars became more dispersed, collective investigation of outstanding problems became rare, as did contacts between scientists in different geographical regions. Furthermore, since the transmission of intellectual tradition at that time relied on communication between master and pupil, over the next several hundred years the most exciting lines of research dried up, and European science fell into a long period of decline.

The above story highlights the importance of a critical mass of scientists in sustaining investigation. To cope with this concern, scientists have created communities via scientific societies, conferences, journals, and electronic networks. A recent use of technology to enhance communication is the World Wide Web, which was originally created by physicists doing research at the CERN high-energy physics laboratory in order to facilitate the exchange of data and ideas. The preceding examples have indicated the importance of communities for the success of scientific exploration.

Relevance of Groups to the Children

Although contemporary historians of science largely agree on the importance of groups and their shared beliefs and practices in science, the earlier view of history of science as primarily a story of individuals is very much alive in many elementary and secondary schools. For example, a gallery of pictures of great men such as Galileo, Newton, Einstein, and occasionally great women — Madame Curie — or persons of color — George Washington Carver — is a familiar sight in classrooms. It is also present in textbooks, which typically portray science ahistorically, that is, as a collection of facts or scientific truths. Even when textbook writers do bring in an historical perspective, they usually emphasize one or two outstanding scientists and rarely mention the intellectual movements, laboratories and research teams of which they were part.

The sixth graders in this class were involved in a science learning environment that emphasized group work and interactions, in contrast to the stress placed in many science classrooms on individual work. The teachers, Dave and Tanya,[13] stressed a "sense-making" approach (Rosebery, Warren & Conant, 1992) to science, which emphasized gathering data through: pooling initial ideas; using shared tools such as Sundial, a program that gave the sun's location for any time and location; experimenting with materials; sharing hypotheses and explanations; making counterarguments; and trying to reconcile diverse points of view. All of these activities took place in the context of small group explorations, work in pairs, or whole groups discussions. Small groups typically reported their findings back to the whole class, and classmates sometimes offered them feedback. The children also participated in an electronic news group with a class of children in New York who were also exploring the relationship between the movement of the sun, shadows and the seasons. In addition, I worked with some of the children in small groups and pairs to

[13]Fictitious names are used for the teachers and the children.

explore topics of their own choosing. In short, therefore, there were many opportunities to observe the children exploring in the context of a group.

The children functioned like scientists in groups in a number of ways. At times, working in groups allowed them to divide up tasks and make use of each other's specialized knowledge or skills. As noted in the section on contradictions, group members gave each other feedback on their ideas. When ideas were challenged, they sometimes became more fully articulated; at other times, they lost adherents. This dynamic interchange helped energize and sustain investigations. The children also benefited from shared beliefs and practices. The learning and using of a vocabulary specific to their field of investigation (e.g. length of day, altitude, terminator) helped them communicate their ideas more precisely. They made use of tools like Sundial to generate data and test hypotheses. Finally, their efforts were unified by a common agenda — finding the connection between the sun's movement and the time of year.

This section has indicated why attention to groups and their shared beliefs and practices is important for understanding and facilitating children's science learning. In contrast, the emphasis in traditional classrooms is on the acquisition of knowledge and skills by individuals.

Preview of Core Chapters

The following section previews the core chapters of the thesis. Each chapter addresses an activity important to science in the making, and identifies ways that children involved in science exploration encounter challenges similar to those faced by professional scientists.

Questions and Contradictions

This chapter focuses initially on roles questions play in motivating and sustaining investigation. The heart of the chapter is an analysis of questions of a particular kind — those that address a conflict between a previous experience or belief, and an event that is being observed or reflected on. This analysis highlights two similarities in the question-asking activity of children and historical scientists.

First, both use similar processes and skills to identify contradictions. These include drawing on relevant facts, ideas and frameworks that others may overlook, and considering the significance of special cases. Second, for both children and scientists, background influences serve as interpretive frameworks that shape whether or not a contradiction is perceived. This is demonstrated through examples, particularly those which require taking background influences into account in order to make sense of the question.

Constructing Definitions

The process by which the terms used in scientific investigation are defined is an important part of science in the making, although it has not yet gained the attention of science educators. This chapter identifies salient aspects of constructing definitions which can be found in the explorations of both scientists and children.

Determining the *scope of a term* — deciding which things it includes, and which it does not — is key to constructing definitions. Methods of determining the scope of a term include establishing exemplars, careful analysis of borderline cases, and developing evaluation or membership criteria. The history of defining syphilis will show how, at various points in time, the scope of the term both reflected the impact of background influences and affected how successfully the disease was detected and treated.

The process by which a definition is *operationalized* is another important aspect of constructing definitions. An operational definition takes a distinction that may be clear conceptually — e.g. a sterilized medium is one that contains no life — and defines it in a practical way — e.g. a growth medium has been *sterilized* when it has been boiled in water for fifteen minutes. I analyze an historical debate over spontaneous generation to illustrate the complications that can arise when the operational definition does not have the intended scope.

Several learning stories are analyzed to reveal the children's capacity for constructing definitions. The stories concern a series of experiments designed to determine whether girls have a better sense of smell than boys, and investigations of the questions, "What is intelligence?" and "What is a shadow?" Group interaction features prominently in these stories.

The Use and Interpretation of Models

The learning stories in this chapter concern the children's use of models to explore the phases of the moon. In contrast to the process of constructing definitions, the use and interpretation of models has been a focus of attention for cognitive scientists and science educators. However, the frameworks used to analyze the learning stories are not those common in the literature (such as whether they are physical, computational or abstract). One such framework is the distinction between *ready-made models* and *models in the making*, which is defined by analogy to that between ready-made science and science in the making. A second distinction is drawn between *surface models,* which capture only the appearance of the things modeled and *explanatory models,* which explain how they work. The analysis in this chapter, as in previous chapters, shows how the children's thinking and activity is shaped by background influences.

Motivations Underlying the Research

The goal of this dissertation is to identify similarities between the practices of children and scientists. This agenda was motivated by observations I made during previous work with children. For example, it was striking to me that although numerous studies deplore American children's poor performance on standardized tests, children are remarkably competent when they explore and problem solve in contexts they find meaningful. This became especially apparent to me as I worked with children engaged in science explorations and constructionist learning projects using Logo and LEGO/Logo. Children frequently generated intriguing questions or initiated creative projects. They also identified and often overcame challenges along the way. However, because of constraints such as limited knowledge or inadequate tools, their success was at times only partial, and their competencies were not always reflected in their contributions to class discussion or the artifacts they produced. Thus, the dissertation research grew in part out of a desire to systematically identify strengths in children's thinking and activities that may easily go unrecognized.

The viewpoint of the thesis was also informed by my previous findings concerning children's ideas about the nature of science (Brandes, 1996). As I explored children's ideas about science, such as what scientists do and how experiments lead to novel discoveries, it became clear to me that the children were mystified by many aspects of science, particularly those concerning science in the making. Furthermore, it was not surprising that their school science experiences were not helpful in this regard, because many of their elementary school teachers also had a limited understanding of the nature of science. Thus, a second motivation for identifying and articulating the similarities between the practices of children and scientists was a desire to find ways to help children and teachers better understand the nature of science.

My current formulation of the dissertation framework evolved through discussions with David Hammer, who suggested that I make the similarities between the practices of children and scientists the central concept. The phrase "seeds of science practice" comes from "Student Inquiry in a Physics Class Discussion" (Hammer, 1995), in which he also refers to these similarities in practice as "nascent science."

Seeds of Science — What About the Differences?

The phrase "seeds of science practice" acknowledges that in most cases the children's activities are different from the corresponding activities of professional scientists. This is not surprising, because there are many differences between the circumstances under which children and scientists conduct inquiry. For example, scientists are part of a professional discipline and have mastered both tacit and explicit knowledge which has proven valuable in finding and solving the types of problems in which they are interested. In terms of the themes discussed earlier, professional scientists have a much stronger and more specialized foundation of ready-made science.

Another important difference is that professional scientists generally have a higher degree of commitment to thoroughness and completion in their explorations than do children. Among the reasons for this are that professional scientists have exercised much greater choice in selecting specialties that match their interests and abilities, have a greater stake intellectually, emotionally and financially in the investigations they undertake, and know that their work will be evaluated with respect to its accuracy and persuasiveness.

Because of these differences teachers, who face practical challenges on a daily basis, might question the value of an approach that emphasizes the identification of features of children's science practice— the seeds of science practice— that are similar to those of professional science practice. I offer two brief responses to this potential challenge.

First, the benefits of the framework hold despite the differences. For example, familiarity with the science activities that are analyzed as part of this framework might enable a teacher to recognize in children's activity an attempt to delimit the scope of a term that is key to their science exploration, and not dismiss it as irrelevant banter. She might also be able to understand some children's ideas that she initially finds puzzling if she takes account of their background experiences and beliefs. Such understanding is valuable knowledge in the hands of a talented teacher. Since the teacher does not expect the children to be acting exactly like professional scientists, such differences need not limit her ability to respond to the situation productively.

A second, and stronger, claim is that the differences can provide teachers with additional information helpful for achieving two goals: understanding the nature of science, and facilitating children's science learning and exploration. Practices characteristic of scientists may become more evident by contrast with those of children. For example, as was sketched earlier, children can construct arguments which have initial plausibility by finding a mechanism that can produce the observed effect (distance from a source affects temperature) and a "fact" that makes it relevant (the elliptical orbit of the earth as frequently portrayed in books). This is, to a limited degree, similar to a scientist's construction of a causal argument. However, it overlooks an objection that may be obvious to other children in the room, namely that the seasons are opposite in the Northern and Southern Hemispheres. This might suggest that scientists, in contrast to children, characteristically anticipate possible challenges to their ideas. A teacher may then find ways of encouraging children to more habitually connect their new ideas and understandings to more established ones.

An awareness of differences between children and professional scientists can also prove valuable when facilitating children's exploration or designing learning environments. Among the ways a teacher might put these ideas to work is to: teach children how to locate relevant explicit bodies of knowledge; provide opportunities to gain understandings that are usually tacit for scientists, but absent in school science, such as the interpretation of models; gather resources such as instruments and tools for making instruments (Resnick, 1996); and set up participation in groups of different kinds.

In short, consideration of the differences between children and professional scientists can help increase one's understanding of the nature of science, set goals for improving children's "science skills," facilitate children's science explorations, and create effective science learning environments.

Summary

This dissertation seeks to identify the strengths of a group of sixth-grade children's science inquiry process by identifying similarities between their practices and those of professional scientists. These similarities, called here "seeds of science practice" are the organizing principle of a framework that includes themes (such as science in the making) and activities (such as "constructing definitions") to which the themes are applied.

The themes serve as lenses for focusing our attention on the positive aspects of children's science practice. An example mentioned earlier is the children's idea that the seasons are caused by the earth's changing distance from the sun. Their reasoning becomes more understandable to us if we consider two important background influences—children's experience with heat sources, and their familiarity with pictures depicting the earth's orbit as highly elliptical. This example also reflects an emphasis on science in the making, in contrast to ready made science, and highlights the importance of contradictions and the role of the group.

In contrast to the themes, which recur throughout the dissertation, each activity — generating questions, constructing definitions, and using and interpreting models — is the focus of one of the core chapters. These activities lend structure to the search for children's science accomplishments. They suggest, for example, that in addition to focusing on science in the making or taking account of background influences, one should pay attention to specific activities, such as the process of how terms are defined. Additional levels of detail are used to further articulate the activities. The concept of "delimiting the scope of a term," for example, contributes to a more detailed account of how definitions are constructed.

The core of this dissertation is its analysis of student inquiry, presented as learning stories. Although the presentation in this chapter emphasizes the framework in its ready-made form, I hope that the learning stories will highlight the grounding of the framework in observation and will allow glimpses of its evolution as science in the making. My intention is that the resulting conclusions both reflect the learning that took place in this particular classroom, and provide a conceptual framework that can be adapted for use in a wide range of settings.

Chapter 2: Literature Review

Introduction

This chapter situates the dissertation research with respect to related literature. The discussion begins with literature that addresses the situated and social aspects of cognition, and which emphasizes the similarities between everyday and expert learning and activities. These similarities are particularly striking when contrasted to the learning and activities that typically take place in school. As will be explained, these similarities are relevant for comparing the science practices of children and professionals.

The focus on seeds of science practice implies a concern with the process of development, and this dissertation takes a constructivist approach to learning. The next section, therefore, addresses constructivist ideas about development and learning. Because there are many approaches to education that are called constructivist, the dissertation research is further situated by its contrast with the "misconceptions" approach to science education and its proximity to "constructionism" (Papert, 1991). The final body of research discussed, which is closely related to the themes and activities central to the dissertation research, involves the role of "the nature of science" in science learning.

Situated and Social Cognition

In many schools, science is presented as a body of factual knowledge. Students are expected to learn to recognize and solve specific types of problems by using a limited set of algorithms, and emphasis is placed on the hypothetico-deductive or inductive thinking that is sometimes said to characterize "scientific thinking." In describing children's science thinking and activities as "seeds of mature science practice," I am taking a very different approach, one that has affinities to the "new epistemology for learning" articulated by John Seely Brown (1989).

Brown argues that there are striking similarities between everyday and expert learning activities and reasoning processes, especially in contrast to the learning and thinking that takes place in most schools. For example, he writes that although traditional school learning is focused on individual cognition, both everyday and professional learning settings are more typically characterized by social interaction. He also points out that in school there is often an emphasis on the manipulation of symbols, or facts, in a manner which does not connect to the rest of children's experiences. Brown notes that in everyday reasoning (e.g., when following recipes, or fixing a broken car door), "just plain folks" (JPFs) Lave (1988), make use of objects and symbols that are closely linked to their daily experience. Like JPFs — and unlike students — experts engage in activities that are bound to genuine experience and motivated by their personal interests.

> It can also be argued that, unlike students, both (JPFs and experts) have their activities situated in the cultures in which they work, within which they negotiate meanings and construct understanding. The issues and problems that they face arise out of, are defined by, and are resolved within the constraints of the activity they are pursuing. Students, by contrast, are generally expected to behave entirely differently. Usually it is only in the final stages of graduate education, when students come to do independent research in the community of scholars, they move from the in-school world of laws, symbols, well-defined problems, and so forth, to the out-of-school world that circumscribes the activities of both JPFs and experts (Brown, 1989, pp. 13-14.)

Although educators may be motivated by the desire to make learning transferable, reproducible and testable, when they decontextualize it, they rob it of many of its essential features. For example, because most physics problem solving is not linked to real-life experience, students frequently ignore their own intuitions and "common sense" when doing course work (Hammer, 1991). Another consequence of this disjunction between school and everyday life is that while many children are interested in science-like activities. such as observing earthworms or exploring magnets (Rennie & Parker, 1987), they often view school science as difficult and uninteresting.

In order to help position my work, I will address three issues raised by Brown: the role of culture, everyday thinking, and problems that are not well defined.

The Role of Culture

Brown notes that the activities of both JPFs and experts (JPFs include children not in "student-mode") are situated in relevant cultures which offer them support and feedback.

He argues that because in school many artificial boundaries have been drawn between subjects and between learners, the culture of everyday life is a more appropriate environment for children's learning. This view is consistent with Papert's (1980) idea of "learning cultures," modeled after the Brazilian "samba schools," in which participants with a common interest, but of diverse ages and skill levels, can work and learn together. (As described by Bruckman (1997), electronic communities have proved to be excellent environments for supporting such cultures.)

The role of culture is reflected in two of the themes used to analyze the data in this dissertation: the role of the group and background influences. The focus on the role of the group in the dissertation highlights both the benefits for children of working collaboratively and the way that scientists are supported by the shared goals, ideas and methods that constitute a paradigm or research programme. The theme of background influences is relevant to groups because tacit knowledge is often learned through a process of enculturation. (In contrast, the emphasis in most science classrooms is on explicit knowledge of facts.)

One process of enculturation by which novices gain expertise has been called "legitimate peripheral participation" by Lave & Wenger (1991), a phrase that includes the idea that a learner "who participates in the actual practice of an expert, but only to a limited degree" is, nevertheless, involved in *legitimate* activity (p. 14). Their analysis includes cases such as the apprenticeship of Vai tailors in Liberia and individuals learning to become non-drinking alcoholics through Alcoholics Anonymous. Although the goal of science educators in the elementary and secondary schools is not to turn children into scientists in a specialized discipline, the metaphor "seeds of mature science practice" shares with Lave and Wenger the idea of legitimacy. It conveys the idea that some of what 6th graders do in the context of science learning is a legitimate, albeit nascent, form of science practice with the potential to develop into a more mature form.

Everyday Thinking

Another similarity between the approach taken in the dissertation and that articulated by Brown (1989) is that both see the children's science activities as the application of everyday thinking skills to problem solving rather than as the application of specialized "scientific thinking skills." This view contrasts with that of other educators, who see particular thinking skills as critical. For example, in their book *The Development of Scientific Thinking Skills* Kuhn, Amsel, and O'Loughlin (1988) emphasize the differentiation of evidence from hypothesis. The work of Inhelder and Piaget (1958) on hypothetico-deductive reasoning and the control of variables is also seen by some educators as crucial to "scientific thinking," i.e., they emphasize the way in which a lack of such reasoning ability may constrain children's ability to do science. For example, in his history of ideas in science education, DeBoer (1991) includes a section called "When are Students Ready to Think Like Scientists?" in which he addresses the implications for classroom science of Piaget's ideas about formal operations.

In contrast to the above views, my focus on specific activities that I see as important for science inquiry and which do not appear to require a special kind of thinking. A similar parallel between the processes of children and experts doing mathematics and science is addressed by Smith, diSessa, and Roschelle (1993). One of their examples is that when simplifying fractions, neither children nor mathematicians adhere to a school-like approach. Rather, both apply strategies of their own. Although the strategies of the children are sometimes incorrect (i.e., they yield wrong answers) or applied inaccurately, or inappropriately children resemble mature mathematicians in their tendency to use their own specialized strategies rather than the more general but often less efficient strategies they are taught in school. Thus a focus on activities rather than results highlights the use of everyday thinking in the pursuit of science.

Problems That Are Not Well-Defined

Brown asserts that in school, children are usually given "well defined" problems to solve, which are very different in character from those encountered in both the everyday world and in professional contexts. In performing school science experiments, for example, they are often told which quantities to vary, how to make measurements, and which graphs and charts to produce. In the out-of-school world, however, there are many ways in which problems are *not* well defined. Coping with these problems is a key challenge in doing science. The learning stories analyzed in this dissertation highlight ways in which children involved in science inquiry grapple with these difficulties. For example, finding an adequate definition can be a significant and ongoing challenge in a scientific investigation. This will be illustrated in chapter 5, through historical examples such as the changing definition of syphilis, as well as the children's discussion of intelligence.

Constructivism

"Constructivism" is a widely used term that refers to ideas and beliefs about development, education, epistemology, and the nature of reality. Most constructivist ideas about development grew out of the work of Jean Piaget (1929; 1954; 1970). In its most basic form, constructivism describes a model of human cognitive growth as a process of progressive adaptation in which successively richer understandings of the world are built up through a process of *assimilation* and *accommodation.* When one experiences something, it may be assimilated, i.e., interpreted in terms of one's current construction of the world or one's current understanding may be changed (accommodated) to better fit the novel experience. Although some form of constructivism is widely accepted among psychologists, cognitive scientists, and progressive educators[1], as will be noted below,

[1]Many of Piaget's ideas such as those concerning stages of development remain controversial with respect to their validity, importance and implications. For an analysis of the "hard" and "soft" cores of Piaget's research programme, see (Groen, 1978). Among the constructivist points of view of development are the "neo-Piagetians," who incorporate some stage-like concepts (Case, 1985; Feldman, 1980; Fischer & Pipp, 1984) and those who focus on the development of concepts within particular domains (Carey, 1991; Chi, 1992; Smith, Carey, & Wiser, 1986; Wiser, 1988). Computationally based or inspired models include

much educational practice is based on empiricist (e.g., Skinner, 1968) or innatist (e.g., Fodor, 1983) views.

Although the prolific Piaget wrote very little that specifically addressed education (Piaget, 1970b; 1973), many educators have developed approaches based on his work. Even early efforts to apply Piaget's theory to education took radically different forms. Some, for example, set progression through specific stages as the goal of learning (e.g., Engelmann, 1971; Furth & Wachs, 1974) while others focused on providing children with the opportunity to construct their own understandings (e.g., Duckworth, 1987; Kamii, 1973; Kamii & DeClark, 1985). Despite the diversity of approaches, all constructivist educators share the belief that knowledge is built, over time, through an interaction between the child and her environment. They assume that because learning involves the modification of current understandings, rather than a simple acquisition of facts, a mode of instruction that is based on a straightforward transmission of information is at best ill-advised and at worst doomed to failure.

Constructivism and Science Education

Like other content areas, science education has been heavily influenced by constructivist theories of development; as is the case in other domains, educators emphasize different parts of these theories and draw a range of implications from the parts they choose. Many constructivist science educators see themselves as an enlightened and embattled minority, opposing those who hold a transmission view of science education. For example, James Gallagher (1993), an educator who has researched teaching paradigms in secondary science for the past ten years, writes that teaching continues to be equated with transmitting information to students. In his view, most teachers still believe that

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those of the "information processors," who use methods such as production systems (Klahr, Fay, & Dunbar, 1993; Klahr, Langley, & Neches, 1987; Siegler, 1984), as well as those which treat human cognition as a parallel process, such as the "Society of Mind" model of Minsky and Papert(Minsky, 1987), and the perception microworld of Drescher (1991).

learning is about acquiring transmitted information, often through memorization (p. 181). Gallagher goes on to write:

> This paradigm is so commonly practiced in secondary school and university science classes that other paradigms are of only minuscule influence. For most secondary science teachers in the United States, the behaviorist-positivist tradition, which underlies this paradigm, has been deeply ingrained in their own education, both in science and in teaching. This tradition has been such an integral part of the scene in education in the sciences from primary school through college as to render alternatives, such as constructivism, strange and often unwelcome (Gallagher, 1993, p. 181).

In describing the opposition between the transmission and constructivist views on a mental level Cobern (1993) writes that "Learning is not knowledge written on or transplanted to a person's mind as if the mind were a blank slate waiting to be written on or an empty gallery waiting to be filled." His view of constructivism emphasizes the influence of prior knowledge in the construction of new knowledge. "Learning by construction thus implies a change in prior knowledge, where *change* can mean replacement, addition, or modification of extant knowledge" [emphasis in the original] (Cobern, 1993, p. 51).

This view underlies the position of many researchers interested in "conceptual change." Research on what has been variously called "misconceptions," "preconceptions," "alternate frameworks," or "children's ideas" has identified ideas children typically hold about topics in science, which, although they may not be as explicit or coherent as formal theories, are robust and may persist despite school instruction (e.g., Carey, 1991; Driver, Guesne, & Tiberghien, 1985; Osborne & Freyberg, 1985; Posner, Strike, Hewson, & Gertzog, 1982). Like misconceptions researchers, I believe that these ideas have a profound effect on children's science learning. Where I differ from them is in the implications I draw from these insights into children's ideas and thinking.

One way I differ is that I do not hold the "replacement" model of learning that many misconceptions researchers hold either explicitly or implicitly. For example, Cobern (1993) states that "conceptual [change] research is important to constructivists because learning is viewed as a process of deconstructing misconceptions and reconstructing valid scientific conceptions in their place" (p. 54). This is because, in the language of philosophers of science, theory is underdetermined — there can be many theories that are compatible with the evidence. From a constructivist developmental position, therefore, there are alternatives to the idea that learning requires deconstruction and reconstruction. This model of learning does not follow necessarily from a constructivist developmental position. For example, in a Society of Mind model (Minsky, 1987), learning can involve the acquisition of new "manager" agents, which take note of, but may overrule, the decisions of agents that embody the previous understanding.

Furthermore, the rhetoric and strategies of many misconceptions researchers seem to be at odds with the constructivist view that understanding develops from an interaction between current knowledge and experience. Smith, diSessa, and Roschelle (1993) express a similar critique "it is difficult to see how misconceptions that (a) interfere with learning, (b) must be replaced, and (c) resist instruction can also play the role of useful prior knowledge that supports students' learning" (pp. 123-124).

This is an important critique because, even researchers who express an appreciation of children's thinking view children's ideas as obstacles to scientifically correct understanding and emphasize the need to rid them of their incorrect views, (McCloskey, 1983; Posner, et al., 1982; Sadler, 1992). Sadler (1992), for example, writes that it is unfortunate that the term "misconception" can seem to denigrate children's ideas, since "After all, it is wonderful that students do come up with such amazing and original constructions" (p. 2). However, he also writes that an important educational goal is to change curricula so that "misconceptions may be more efficiently replaced by scientific conceptions" (p. 55). Until text books pay closer attention to students' misconceptions, "students are damned to try to place new conceptions upon faulty foundations" (p. 243). Similarly, a widely cited paper by Posner, Strike, Hewson, & Gertzog (1982) recommends that teachers "organize instruction so that [they] can spend a substantial portion of their time in diagnosing errors in student thinking, and identifying defensive moves used by students to resist accommodation" (p. 226).

In contrast, my point of view is that the primary value for educators of understanding children's thinking and activities is to help them find ways of nourishing the growth of their seeds of science practice, not to replacing children's ideas with "correct" ones.

Constructionism

A specific form of constructivism — *constructionism* — will be used in the dissertation to analyze the children's activity, particularly their work with models. This approach has been articulated by Seymour Papert and developed through the work of the Epistemology and Learning Group at MIT (Harel & Papert, 1991; Kafai & Resnick, 1996; Papert, 1991).

Papert (1991) writes that *constructionism* adds to the constructivist view of learning as a process of "building knowledge structures" the idea "that this happens especially felicitously in the context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach, or a theory of the universe" (p. 1). In the analysis of the children's model building, the constructionist aspects that will be emphasized include: the necessity of making details explicit the way conscious engagement mobilizes personal knowledge, the value of feedback, and other affordances of public accessibility.

Connectedness

A theme that is closely related to constructivism and constructionism is connectedness. Connectedness emphasizes the importance to learners of building links between their current ideas and experiences and new areas of interest. This theme is not new in education. Dewey (1916) claimed that it was important to relate new ideas to something the student already knows, or else to provide the student with relevant experience. "Avoid isolation in all forms," he wrote some years later. "Strive for connectedness" (Dewey, 1938). However, new computational media provide new opportunities for building connections. Furthermore a recent epistemological view articulated by Ackermann (1996), holds that knowledge is relationship. She argues that knowing can be viewed as a process of dancing with the world.

One source of connectedness is the mapping of a familiar body of knowledge onto a new or less familiar domain. Papert (1980) describes how "body syntonicity" can help children write LOGO programs to draw geometric shapes. For example, if a child desiring to write a circle-drawing program were encouraged to "play turtle" by walking slowly in a circular path, she might realize that she was repeatedly taking a small step and then making a small turn, a procedure she could translate almost directly into a LOGO program.

Wilensky (1993) has developed a constructionist approach to mathematics learning, called "connected mathematics," that makes connectedness a central theme. The analysis in chapter 6 will apply to the use of models several of the principles he emphasizes, such as the importance of multiple representations and the value of building links between different pieces of understanding. Additional elements that may facilitate connectedness include mapping a phenomenon that is difficult to visualize onto a more tangible one, identifying as a participant in a situation you are trying to understand, and first thinking about specific cases.

The Nature of Science

Educators and researchers have recently argued that understanding "the nature of science" is an important part of science learning (AAAS, 1993; Aldridge, 1992; Driver, Leach, Millar, & Scott, 1993). It is claimed that educators must address epistemological questions such as "what is science?" "what is the nature of scientific knowledge?" and "what are the roles of theory and experiment in science?" in order to provide children with a much richer and more accurate understanding of how science actually works.

The AAAS (1993) divides the nature of science into three main areas: the scientific world view, the scientific enterprise, and scientific inquiry, which is the focus of this dissertation. In discussing scientific inquiry the AAAS emphasizes the following points: "science demands evidence"; "science is a blend of logic and imagination"; "science explains and predicts"; and "science is not authoritarian" (pp. 4-7). In contrast to more rigid descriptions of "scientific method," they note that "there simply is no fixed set of steps that scientists always follow, no one path that leads them unerringly to scientific knowledge" (p. 4).

The AAAS emphasizes the role of hypothesis formulation and hypothesis testing.

> Scientists do not work only with data and well-developed theories. Often, they have only tentative hypotheses about the way things may be. Such hypotheses are widely used in science for choosing what data to pay attention to and what additional data to seek, and for guiding the interpretation of data. In fact, the process of formulating and testing hypothesis is one of the core activities of scientists (AAAS, 1990, p. 4)

Although this view represents an improvement over many current textbooks, it would probably be grouped by Carey et al., (1988) with viewpoints that fail to pay sufficient attention to the important role played by theory. For them, the role of theory in guiding the day-to-day activity of scientists is critical.

> Exactly what view of the nature of science do we wish to give to students? It is common practice for current textbooks to portray scientists as engaged in a process which depends upon careful observation and experiment, and to teach students some of the skills involved in careful experimentation. However, overlooked in these accounts is any discussion of the role of the scientist's *theories* in this process. Instead, mention is only made of scientist's specific *hypotheses* or beliefs about the world. In some accounts, these hypotheses are seen to be a simple consequence of unbiased observation and experiment, while in others it is acknowledged that scientists may have hypotheses which motivate their doing a particular experiment. However, in either case, these hypotheses are thought to be tested in unproblematic and straightforward ways by the data of critical experiments, and scientific knowledge is portrayed as the steady accumulation of a set of confirmed hypotheses. As Hodson (1985, 1988), Nadeau & Desautels (1984), and Strike and Posner (1985) claim, such a view is essentially an inductivist or empiricist view: The origin of scientific knowledge lies solely in data about the world.
>
> We would argue (along with the above-mentioned authors) that it is important to present students with a more constructivist epistemology of science: one in which students develop an understanding that scientists hold *theories* which can underlie the generation and interpretation of specific hypotheses and experiments. We want them to come to understand that our knowledge of regularity in nature is a consequence of successful conjecture rather than its precursor and that an adequate theoretical perspective is essential to both observation and experimentation. Thus, without challenging students' faith that theories may ultimately reflect reality, we may be able to help them see that theories are large-scale intellectual constructions which constitute the scientists' understanding and guide the day-to-day activities of scientists. Such an understanding would help students understand why scientists do experiments, why there can be legitimate controversies in science, and even why learning science is difficult. [emphasis in the original] (Carey, et al., 1988, pp. 3-4)

A difference between the emphasis in this dissertation and that of some researchers interested in the nature of science is the central place given by them to the role of theory as an intellectual framework (Duschl, 1990; Duschl & Gitomer, 1991; Hodson, 1985;

Hodson, 1988). Although I agree that theory is important in the practice of science, I believe, as noted in the introduction, that background experiences and beliefs, which are often of a more informal nature, play a parallel role for children. Learning stories in the dissertation will show how these background influences shape children's science inquiry activities such as the generation of questions and the construction of definitions. The focus of my analysis is on issues important to the nature of science that are *already present* in the children's science inquiry. In contrast, writers such as those cited above address the characteristics of science practice that they believe children (and college students) *should understand.* Consequently their emphasis is on the construction of curricula to teach about the nature science.

My dissertation research shares several features with the work of David Hammer (1995). In his analysis of science inquiry in a high school physics class, Hammer (1995) writes that we must "look for the beginnings of scientific inquiry in what students already know how to do" (p. 405). (As previously stated, the concept "seeds of science practice" originates in his work.) He notes that what is valuable in the students' process is not always as tangible as the flaws in their conclusions, and he uses a careful analysis of what they say and do to identify their strengths. Although Hammer notes that his analysis is influenced by theory, the starting point of his work is his observations of classroom discussions rather than a theoretical model of mature scientific reasoning. Similarly, the themes and activities that make up the framework described in this dissertation grew out of my observations of children's discussions and activities, and not an *a priori* model. As noted in the introduction, these themes and activities are tools with which to identify the children's strengths.

Chapter 3: Methods

Choosing the Research Site

Rationale

I undertook this research in order to identify abilities that children bring to productive scientific inquiry. Rather than create my own program which would tie up time and energy I could more profitably devote to observing and analyzing the children's activities, I sought an existing classroom setting that provided a rich inquiry environment. My desired research role was that of a participant observer — a researcher actively involved in the setting, rather than observing it from a distance. For me this meant working with a teacher who would use me as a resource in the classroom, talk to me about the curriculum and the students, and facilitate arrangements for me to interview the children, and work with some of them in small groups.

I decided that a sixth or seventh grade classroom would be the most appropriate for my study. In part this is because of how school science instruction is scheduled in schools. In the later grades, children "travel" to a science teacher's room, and may not be together at any other time of day, which would make working with them outside of science class difficult. Furthermore, there is typically more pressure to cover particular content material in the older grades, leaving less time for science inquiry. I chose not to work with younger elementary school because they generally have fewer relevant experiences and skills to draw on, and because I believed it would be difficult to locate an appropriate classroom.

In addition, I thought that a good inquiry environment might make a noticeable difference for middle-school children, because they have been found to hold epistemologically naive views about science, but have demonstrated the capacity to increase the epistemological sophistication of their views in conjunction with a curriculum on the nature of science (Carey, et al, 1989).

My goal, therefore, was to find a middle school classroom with an excellent inquiry-based science curriculum, a cooperative teacher, access to the classroom activities, and opportunities to interview children and work with them in small groups.

The Search

The school in which I was working ended with the fifth grade, and did not have a science program that included sustained inquiry. I needed, therefore, to search elsewhere for a research site. Locating a site that provided the kind of learning environment I was seeking, however, was not easy. After consulting with a variety of education professionals in the public schools, at education research centers, and at MIT, Harvard, and Tufts, I compiled a list of recommended teachers who had put significant effort into creating or adapting a curriculum and establishing an environment supportive of inquiry. I met with eight teachers in person, and observed their classes. In addition, I talked with and screened several others by phone.

All the teachers were using curricula that were much more engaging and worthwhile for the children than typical science curricula; nevertheless, for various reasons, few of them met my research needs. For the purposes of my research it was important that the children have opportunities for sustained, open inquiry. However, in a number of these curricula, many of the "in-the-making" aspects of the activities had been taken care of in advance, i.e., the variables had been specified, as had the quantities to be measured, the methods to be used, the combinations of materials to employ, and the organization of the data. Hence, although many of these classrooms may have provided an excellent science learning environment, they were not appropriate for me because I wanted to observe the children's investigations in a less constrained setting.

A variety of practical considerations also led me to eliminate some classrooms. For example, because most of the teachers only taught science, and had the children in their room for only one block of time a day, which would have made interviewing or conducting small groups difficult. One teacher did not want me in the classroom during an extended time period when a student teacher would be in charge. This process of elimination led to my selection of the potential research site that seemed most promising.

The Research Site

School/Classroom Overview

This research was conducted in a sixth-grade classroom in a public school in the Boston area. The school is noted for its innovative curriculum, and attracts students from varied socio-economic backgrounds. The classroom teaching is shared by two teachers (who I will call Dave and Tanya), each of whom teaches two fixed days a week and alternate on the remaining day. They both have nearly twenty years of teaching experience and have developed many learning activities, some in conjunction with researchers from the local educational community. Furthermore, they have chosen to work in a school that gives them great freedom in organizing their classroom activities. The children in their classroom are engaged in individual, pair or group activities, or teacher-facilitated whole class discussion. As was described in the introductory chapter, their work in science emphasizes the importance of "sense-making" by the children (Crowder, 1996; Jackson, 1992; Rosebery, Warren, & Conant, 1992) .

Negotiating Entry

Researchers not only select research sites, they must be accepted at the sites. The teachers at the site I selected had abundant material and human resources (e.g., a part-time assistant, a student teacher, the school science resource person, and, for special events, parents of students), and were well known to educational researchers. This allowed them to be highly selective with regard to their participation in research, and they needed to be convinced that my project would be beneficial to them and to their students. They asked me questions about my research, my willingness to participate in their regular science activities, and observed my interactions with children during a computer-based math activity. I also met with the principal, who, in keeping with the philosophy of the school, said that he would follow the teachers' recommendation. Finally it was necessary to gain the confidence and cooperation of the children. This process began when classes resumed in January, and I began participating in the classroom and conducting interviews. All but one of the children were cooperative in this initial phase.

Subjects

The subjects were the entire sixth-grade class, which was comprised of 13 girls and 12 boys. 14 of the children were European American, two were African American, one was Thai, and nine had emigrated from Haiti during their elementary school years and were originally enrolled in a bilingual program in the school.

Curriculum

The classroom teachers had been teaching a "shadows" curriculum for four years. The curriculum focused on the change in shadows and the position of the Sun throughout the year, and their relation to the change of seasons. The children measured their shadows in the schoolyard when weather permitted. They used a computer program (Sundial) to generate information and find patterns relating the length of day to the time of year and location on Earth. They also used models to help construct explanations of these patterns.

Throughout the process, the children were encouraged to raise their own questions and make sense of the phenomena. Often they did this in the context of group discussion. The ability and willingness of the children to articulate their thinking on these complex matters was impressive. Although they sometimes found it difficult to follow the thinking of other children, they were eager to do so, and enjoyed supporting or challenging the ideas of their peers.

This year, as in years past, the curriculum evolved in response to the children's questions and interests. The curriculum was also influenced by new tools, such as the Sundial computer program, variations in the weather, and this year a special celestial event, an annular solar eclipse. In preparation for observing the eclipse, Dave initiated an exploration of the earth-moon-sun system. After the eclipse the focus became the phases of the moon.

In addition to the shadows curriculum, the children participated in a "structures" curriculum that was led by Tanya. Although this dissertation focuses on the shadows and moon curricula, as well as small group sessions I conducted, a question asked in the context of discussing structures is included in the chapter on questions.

Dave and Tanya's Approach to Sense-Making

Dave and Tanya made sense-making a primary explicit goal for their science activities, and specific content learning was secondary. They were not pressured to cover particular content related to shadows the phases of the moon and, although the topic "structures" was chosen from several options newly mandated by the city, Tanya had great flexibility in designing the structures curriculum. The teachers had considerable control over their classroom, and were able to give students the opportunity to continue investigations over a period of months. When circumstances suggested it, they could also allow activities to continue longer than planned. This allowed for sustained exploration and dialogue. (In contrast, some of the teachers I visited had to manage with several forty minute periods a week.)

One way they encouraged sense-making was through the use of a varied set of activities, representations, and formats. Children collected data through "hands on" activities, such as measuring shadows, and through the use of a computer program. Some data was collected individually or in pairs and was personally meaningful (e.g., the length of their own shadows) while other data was generated in the whole class setting (e.g. solar position).

The children made multiple representations of data, such as representing the solar data by length-of-day diagrams, marking the solar path with disks on the classroom wall, and using a three dimensional model. They expressed their understandings through discussion and debate, as well as through movement (e.g., acting out the yearly motion of the sun, earth and moon). For some children, at least one of the approaches made the material accessible. Others, who benefited from more than one approach, were able to make connections between them.

The children were expected to use these explorations as a basis for finding regularities in the phenomena (e.g., the dependence of the length of day on location), make connections to other topics or knowledge, and offer causal explanations. When children articulated ideas, other children could offer supporting arguments or critiques. The teachers generally served as moderators, and rarely commented on the scientific correctness of children's ideas.

Children's sense-making was also supported by the variety of (work) formats. For example, many of the Haitian-American children participated in whole class discussions only when called on by the teachers. However, they tended to be more actively engaged when working in pairs or small groups. Reporting the group's findings to the whole class was another way children were encouraged to reflect and participate.

In addition to being encouraged to identify patterns and offer explanations, the children were encouraged to generate their own questions. For example, one day Dave asked each child to make up two questions about the Sun's path, which they had been exploring in class. One way the teachers demonstrated how they valued the children's questions was to use the questions as a basis for discussion and exploration. A successful example, which led the children to discuss the question, "What is a shadow?" session will be analyzed in chapter 5 on constructing definitions.

The variety of activities in the class was especially conducive to this research, as it allowed me to observe the students engaging with science in many different ways. That, I suspect, is also beneficial instructionally, since a variety of activities provide more opportunities for students with different strengths and interests to succeed.

<u>The Small Groups Sessions</u>

Several of the learning stories analyzed in this thesis emerged in the context of a small group, which was made up of three girls and one boy (who I will call Emily, Lara and Sally and Brad), all middle-class European-American children. We met as a group for three sessions. Lara also had one session with each of the other two girls, exploring why people are so biologically complex and prone to disease, and Emily and Sally conducted a series of experiments.

We began our work together by generating questions through a brainstorming process. Once the topic was established, children were encouraged to state their ideas aloud and I wrote them down. In order to create a safe and creative environment the children were asked not to negate or comment on the ideas of others. We began with an initial brainstorm in which the children generated completions of the phrase "I am curious about ..." Once topics of shared interest were established additional brainstorms were used to generate specific questions.

When we could not conduct a physical exploration, we used a technique I have developed called the "fantasy experiment." The idea of the fantasy experiment is to imagine, in as much detail as possible, how an experiment might be carried out. Because the experiments are designed and carried out in the imagination, children have the opportunity to "explore" questions that are beyond the scope of classroom investigation. The fantasy experiment undertaken by four children was designed to answer the question, "Is there intelligent life in the universe?" In the process of devising several strategies for identifying intelligent life on other planets, the children realized that they would need to clarify the meaning of "intelligence" in order to determine if alien life was indeed intelligent.

Inter-gender teasing in the small group led to questions such as, "why are girls more mature than boys?" The underlying motivation of proving female superiority led Emily and Sally to investigate the question "Do girls smell better than boys?" through a series of experiments comparing the olfactory abilities of the genders.

The small group's efforts to construct a definition of intelligence, and the two girl's smell experiments are discussed in chapter 5.

Data Collection

The data analyzed in this thesis was collected through clinical interviews and participant observation in the classroom. I observed and audiotaped or videotaped most of the science classes. At times, I interacted with small groups, or worked with individual children. I also spoke frequently with the teachers after class, and they occasionally used my feedback to modify class activities. At the end of the school year I conducted interviews with the children, exploring their ideas about the phases of the moon and what they thought about the various science activities. All interviews and class sessions were transcribed. Field notes were also kept about classroom sessions and conversations with the teachers.

Additional Data

Although the results will not be analyzed in the dissertation, I will briefly mention some of the initial data collected. This data included three questionnaires and served several purposes. The questionnaires, particularly the personal one, gave me some points of contact for the initial interview. The interviews gave me an understanding of the children's ideas about and attitudes towards science, as well as a sense of them as individuals.[1] They also gave the children a chance to ask me questions about what I was doing, and for me to establish that I was genuinely interested in them and their thinking.

This data served two main purposes. It increased my familiarity with these particular children, and it potentially allowed me to make comparisons with data I had previously collected and data from the literature. I used an initial questionnaire to learn about the children's preferred activities in and out of school; in addition, I requested that they add anything else they might want me to know about them. This gave me a start on getting to know them, and suggested topics for rapport building during the initial interview.

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[1] A comparison of my observations in the classroom at the beginning and the end of the research would be a good example of how perception is a construct that is strongly affected by background influences. For example, I initially had difficulty distinguishing two blond-haired boys. My first approach was to try to remember which one wore an earring. However, as I got to know them better I found that their interests, personalities and classroom roles were quite different in ways that were already present although not yet salient, in the initial interviews.

For the initial interview I used the *Image of Science* protocol (Brandes, 1996), which explores children's understanding of the nature of science and their attitude towards science. The interview protocol incorporates questions from the *Nature of Science* protocol (Carey, et al., 1989). To draw out the children's ideas and feelings about scientists and science, I used the Draw-A-Scientist task (Chambers, 1983) , and asked the children about their pictures during the interview.

Because many children have greater interest in science topics and activities than they do in school science, I wanted to differentiate the two. The instruments I employed were the *Science Interest Scale* (Rennie & Parker, 1987) and the *Attitude Toward Science in School Assessment.* (Germann, 1988)

Data Analysis

The process of analyzing the data from this research was a long and iterative one, and I will only briefly sketch it. This sketch will help explain the genesis of the themes and activities used in the dissertation, as well as how I chose which data to include.

The preliminary analysis began while data was still being collected. I took notes during and after class sessions, and reviewed transcripts when they were ready. At times I discussed my observations with the teachers, both to seek clarification and elaboration from them, and to offer them feedback I thought would be helpful. Both the teachers and I sometimes modified our plans based on these sessions. Some of the learning stories analyzed in the dissertation emerged during these discussions, and discussions with my committee members and colleagues. The preliminary analysis also provided some guidance for the final interviews.

The next stage involved reading through the transcripts to identify salient learning stories and themes, such as recurring activities, attitudes and epistemological issues. A unifying characteristic of these stories and themes was the identification of points of connection between the children's thinking, activities and attitudes, and those of professional scientists. The themes and stories were then grouped into chapters.

Some of my original ideas for chapters, such as the *role of epistemology*, allowed me to organize the material coherently. However these ideas required further narrowing. One step in this process was the articulation of about two dozen learning stories that fit the current chapters. Some of the stories were brief and involved only an exchange or two in the classroom. Others, such as the smell experiments, were long narratives that contained many episodes and touched on multiple themes. These learning stories were analyzed to identify more specific activities such as *constructing definitions*, and themes such as *the impact of background influences* that were applicable to multiple activities. As I identified parallels between the children's science practice and that of scientists, I found episodes from the history of science to introduce and articulate them. In writing up the learning stories I again consulted the original transcripts. In short, the analysis involved an iterative process of identifying common themes and activities in the transcripts and the learning stories, and making them progressively more precise and coherent.

Conclusion

The selection of a site was guided by the importance of being able to observe and participate in the science inquiry of middle school children. The analysis was an iterative process, and because the data was extensive, it was necessary to exclude many themes, activities and learning stories from the dissertation.

Chapter 4: Questions

"I have no particular talent. I am merely inquisitive."

Albert Einstein

Introduction

Questions play many important roles in science. They are vehicles through which we express our curiosity, wonder, and desire to understand more about the world, and, as such, are often the starting point for scientific inquiry. When these questions reflect deep passion or interest they provide motivation and help sustain investigation. While some questions lead to narrowly focused research, others lead to multiple explorations and spawn further questions.

The central focus of this chapter is an analysis of children's questions. By articulating similarities between the children's process of posing questions, and that of scientists, I show why this question-posing process is a seed of mature science practice. The similarities are of two main types: similarities of motivation and function, and similarities in the thinking that underlies the generation of these questions. An example of a similarity in the function of posing such questions is that for both children and scientists questions that identify contradictions provide feedback that can lead to the improvement of a theory, or a decline in its status.

The key similarity in the thinking that underlies the generation of these questions is the major role background influences, which include experiences and beliefs, play in shaping them. Unless we consider the children's and scientists' background influences, we may fail to correctly understand their questions. This is first illustrated with examples involving scientists who worked within theoretical frameworks that are no longer part of our world view (for the sake of brevity, they will sometimes be referred to as historical scientists), and then with children's questions.

This chapter is organized into an introduction, and two main sections. The introduction addresses two general issues about questions: their role in science, and the importance given to them by progressive educators. The focus then shifts to questions involving perceived contradictions. In one section, I elaborate important features of such questions and their generation using examples from the history of science. The subsequent section addresses the same issues using questions asked by children in grades two to six.

The Roles of Questions in Scientific Investigations

This section anticipates several points of comparison between children's and scientists' questions. It is not an exhaustive treatment of the role played by questions in scientific investigations.

Although Questions Reflect Curiosity, They May Not Lead Directly to Investigations

Questions may reflect curiosity about a topic, but may not lead directly to an investigation because the question poser does not have the opportunity or requisite tools. At the age of sixteen, Einstein discovered a contradiction between Maxwell's electromagnetic theory, and the Newtonian concept of inertial reference frames. His question arose from the paradoxical result of a thought experiment: "If I pursue a beam of light with the velocity *c* (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest" (Einstein, 1969, p. 53). "How could this be?" he wondered. The laws of physics should hold for an observer moving at uniform speed, but a beam of light that behaved in such a manner would be inconsistent with Maxwell's equations. Although Einstein was not able to pursue his question further at that time, ten years later he returned to it, and developed the special theory of relativity.

Asking insightful questions is not the province of genius alone. Salvador Luria reported that the impetus for his ground-breaking work on cell differentiation was prompted by a question he was asked by a taxi driver: "If human life begins as a single cell that then repeatedly divides, how is it that the cells know what to do, so that they don't all come out the same?" (P. Janney, personal communication). Like the taxi driver, children can pose profound questions. However, the knowledge and skills necessary for asking such questions may be different from those needed to answer them. Consequently, children frequently pose questions that are difficult for them to answer. Nevertheless, even though they could not fully answer many of the questions they raised — such as "what is intelligence?" — the sixth-grade children in this study were able to profitably explore some of them, especially when they benefited from the support and collaboration of others. Examples of this type of collective inquiry will be analyzed in subsequent chapters of the thesis.

Questions Can Provide an Agenda for Multiple Investigations

While some questions focus on a single phenomenon, or reflect a transient interest, others may serve as "guiding" questions, which frame an overarching research agenda and generate many sub-questions. For example, shortly after he read Planck's investigations into heat radiation, Einstein realized that classical mechanics raised questions it was inadequate to answer. According to his autobiographical notes:

> My own interest in those years was less concerned with the detailed consequences of Planck's results, however important these might be. My major question was: What general conclusions can be drawn from the radiation-formula concerning the structure of radiation and even more generally concerning the electromagnetic foundation of physics? (Einstein, 1969, p. 47).

One source of guiding questions is contact with powerful ideas, as was the case with the impact of Planck's ideas about the quantization of radiant energy on Einstein, or Kepler's belief that the harmony of the cosmos could be understood in mathematical terms.

Awareness of guiding questions can help us understand the significance of the "subordinate" questions. For example, Kepler's career was driven by one overarching, implicit question: "How can the harmony of the cosmos be expressed in mathematical terms?" This led him to formulate questions such as "How can the orbit of Mars be described in simple geometric terms?" On a more modest scale, one girl's question, "Why can't our bodies be simpler?" generated many sub-questions, such as "Why do we have fingernails?"

Questions Can Play a Motivating Role

As has been noted by progressive educators, children and scientists can be remarkably persistent when they investigate questions they are passionate about. For example, because Kepler's overall quest was to understand the cosmos in mathematical terms, he willingly devoted eight years to his search for satisfactory representation of the orbit of Mars.

Learning stories in which children's energy, motivation, and persistence were evident as they explored their own science questions will be analyzed in the subsequent chapters on "contradictions" and "constructing definitions." For example, two girls conducted three experiments requiring nine planning, preparation, and analysis sessions in order to answer the question, "do girls smell better than boys?" to their satisfaction. This question was important to them because they were interested in showing, for a particular domain, that girls are superior to boys. In order to appreciate their commitment to this investigation, it should be noted that the girls undertook their investigation voluntarily, and they did all the work during their free time at school. Although their effort was not comparable to the magnitude of Kepler's, neither they nor any other children in the class would have pursued an investigation so persistently without a significant motivation.

The difference between guiding questions and motivating questions is that the former stress the power of the ideas and their function as an intellectual framework, while the latter emphasize the affective role questions can play. As the story of Kepler illustrates, a guiding question can certainly be a motivating one. However, a motivating question may lead to a narrow investigation; this was the case with the girls' smell experiments. The girls' question did not become a guiding one. They did not undertake additional explorations about smell or gender differences.

Educators' Emphasis on Children's Questions

Progressive educators have long emphasized the importance of encouraging children to generate and answer their own questions (Apelman, Hawkins, & Morrison, 1985; Dewey, 1959; Duckworth, 1987; National Froebel Foundation, 1966; Papert, 1992). Dewey (1959), for example, asked educators to evaluate their curricula by determining whether or not it "grows naturally out of some questions with which the student is concerned?" (p. 365). Similarly, in her influential essay, "The Having of Wonderful Ideas," Eleanor Duckworth writes about the power of the right question to mobilize children to do their best thinking and learning:

> the right question at the right time can move children to peaks in their thinking that result in significant steps forward and real intellectual excitement; ... although it is almost impossible for an adult to know exactly the right time to ask a specific question of a specific child — especially for a teacher who is concerned with 30 or more children — children can raise the right question for themselves if the setting is right. Once the right question is raised, they are moved to tax themselves to the fullest to find an answer (1987, p. 5).

National science curriculum efforts have stressed that raising questions is an important scientific attitude. For example, Project 2061 sets the following objective for developing scientific habits of mind: "By the end of the second grade, students should raise questions about the world around them and be willing to seek answers to some of them by making careful observations and trying things out (AAAS, 1993, p. 285).

Like these educators, I emphasize the importance of questions as expressions of curiosity, as motivators of student inquiry, and as reflections of an important scientific attitude. This chapter contributes to that literature an analysis of the similar role background influences play in scientists' and children's generation of questions.

Questions from the History of Science

In this section I use examples from the history of science to analyze the posing of questions that involve perceived contradictions. In the subsequent section, I use the ideas developed here to analyze children's question posing.

A major theme of this section is the formative role that background experiences and beliefs play in scientists' generation of questions. As noted in the introductory chapter, unless we understand something of these background influences, which include everyday experiences and observations, popular beliefs and formal theories, we may not fully understand the meaning of the questions, or the thinking that underlies them. In particular, such lack of understanding may preclude us from perceiving the explicit or implied contradiction contained in some questions. As the examples will show, the question and the context in which it is asked may contain clues as to the relevant background influences. For example, the Pythagoreans believed that the heavens produced harmonious sounds, with tones that depended on the distance of the planets from the center of the universe. Comparing their own experience of music with these supposed cosmic harmonies, critics of the Pythagoreans asked the question, "Why can we not hear these sounds?" The contradiction between the existence of the music described by the Pythagoreans and people's inability to hear it was fairly obvious.[1]

In other cases, more complex reasoning was used in generating the question, and multiple background experiences or beliefs were linked to arrive at the contradiction. For example, Ptolemy will be seen to use both Aristotelian physics and everyday experience to challenge the idea that the earth rotates. Another kind of thinking used to identify contradictions involves a detailed imagining of the consequences of an idea or theory. An example of this is Einstein's thought experiment about riding a beam of light.

Aristotelian Physics: The Effect of a Background Belief

Conceptions about the motion of a thrown object provide a rich arena for thinking about the role of background experience and beliefs in the generation and resolution of questions, as the questions in this section will illustrate. We can observe, as did the ancient Greeks, that unsupported terrestrial objects tend to fall to the ground, while celestial objects move continually around the earth. In contrast, effort is required to push a cart, or throw an apple. This was the experiential basis underlying the Aristotelian distinction between "natural motions," such as falling and orbiting, and "forced motions," caused by external forces, such as pushing, which operate by direct contact.

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[1] That volume or pitch were not the difficulty is clear from the response of the Pythagoreans. Their counterargument was that we do not hear the sounds because we have heard them from birth, and have habituated to them.

In the context of Aristotelian beliefs about motion the question, "What keeps a stone in motion once it is thrown?" poses a problem. The problem is that a thrown stone would be considered an example of forced motion, yet there is no obvious external force acting on the stone once it leaves the hand. Aristotle's solution was to claim that as the thrower's hand applies force to the stone it also disturbs the air, and that the movement of the air supplies the external force responsible for the stone's continued movement. However, as the following examples illustrate, thinkers with different theoretical beliefs interpret the situation differently.

For medieval thinkers, such as Buridan, the question, "What keeps a stone in motion once it is thrown?" was also a challenge. However, their explanation differed from Aristotle's. They believed that a stone, once set in motion, possesses "impetus." For them the return to earth of a stone thrown upwards, or the slowing and stopping of a rolling object, was a consequence of the dissipation of impetus.

Practitioners of Newtonian physics would not need to ask what keeps a thrown stone in motion, because, according to Newton's laws, an object in motion subjected to no net force continues in motion indefinitely. In fact, if they were unfamiliar with other theories of motion they might find the question strange.

People today do not hold formal Aristotelian or impetus views. Yet perhaps because many of their daily experiences in a friction-filled world are similar to those salient to early thinkers, their responses to qualitative problems involving motion embody similar ideas. For example, many college students who have studied Newtonian physics respond to questions such as "what are the forces acting on a coin after it is tossed into the air?" in terms that reflect beliefs comparable to those of Aristotle and Buridan (Clement, 1983; McCloskey, 1983; McCloskey & Kargon, 1988). Other studies have indirectly documented the role of real-world experience by showing that explorations in friction-free computer microworlds can lead to an improved understanding of situations such as the movement of a stone after it leaves the thrower's hand (diSessa, 1982; White & Horwitz, 1987) .

These examples show how background experiences and beliefs can affect the formulation and interpretation of questions. The next section discusses questions posed by Ionnes Philoponos, a Byzantine writer of the 6th century C.E., in his commentary on Aristotle's *Physics.* Philoponos accepted the Aristotelian concept of "forced motion," but broke with Aristotle's theory by suggesting that the hand must transfer some sort of incorporeal power to the stone.

What Keeps a Stone Moving Contrary to Its Natural Direction of Motion?

Without an understanding of prevalent beliefs, Philoponos' question, "When one projects a stone forcibly does one compel it to move contrary to its natural direction of motion by disturbing the air behind it?" would seem rather strange. As was noted previously, however, the answer to this question, according to the Aristotelian view, is yes. Philoponos drew on everyday experience to argue that Aristotle's solution to the problem of projectile motion was not believable, because there are no evident disturbances of the air applying sufficient force to the stone.

He sharpened the contradiction between Aristotle's idea and common sense by asking, "what advantage is it for the stone to be in contact with the hand?" (Toulmin & Goodfield, 1961, p. 128). Furthermore, he proposed a thought experiment — if the movement of the air alone is sufficient to propel the stone, why not simply blow on it (or build a machine to do the job). "The fact is, that even if you placed the arrow or stone on a support quite devoid of thickness and set in motion with all possible force all the air behind it, the projectile would still not move as much as a single cubit."

One point of this story is that everyday experience and common sense arguments can serve to help identify inadequacies of a theory. The story also illustrates the way in which background influences can strongly shape which ideas we find understandable or plausible, and what questions a phenomenon or belief will lead us to pose.[2]

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[2]Philoponos did not have a systematic solution to the problem, but his idea that an incorporeal power was transferred to the stone was a forerunner to the idea of "impetus" developed by Buridan and others hundreds of years later.

Why Aren't Birds Left Behind As the Earth Rotates?

In contrast to Philoponos, who found the Aristotelian belief that forced motions must be explained by external forces to be in conflict with everyday experience, Claudius Ptolemy, an Egyptian astronomer who lived in the second century C.E., used this belief to counter the idea that the earth rotates.

The belief that the apparent daily movement of the stars from east to west was due not to the rotation of heavenly spheres, but rather to the rotation of the earth was first proposed by Herakleides of Pontus and later championed by Aristarchus. Refuting these ideas was important to Ptolemy, whose major achievement was the construction of a complex geocentric model of planetary motion. He identified an apparent contradiction involving Aristarchus's ideas and asked, "Why aren't birds left behind as the earth rotates?" Ptolemy's argument rested on both his observation that birds fly as easily east as they do west, and on the Aristotelian belief that the flight of birds was a "forced motion," which demanded an external force. Furthermore, this force could not be believed to be supplied by the earth, because it had no physical connection to birds. The only way for birds to keep up, let alone make eastward progress, would be for them to fly at the speed at which the earth is rotating, which as Ptolemy could have calculated, is about 1000 miles an hour. This claimed Ptolemy, was hardly plausible.

The preceding two examples highlight some variations in the background influences and the kind of reasoning brought to bear on the process of identifying contradictions. The first variation is in the kind of background influences involved. Both men made use of everyday experiences and observations. Unlike Philoponos, however, Ptolemy also made use of a formal theory — that of Aristotle.

The men also used different types of reasoning and argumentation. Philoponos used two approaches. The first approach was to juxtapose the claim that disturbances of air were responsible for the continued movement of the stone with the everyday experience of throwing a stone; the resulting contradiction was evident . The second approach was the use of a thought experiment, blowing directly on the stone, to isolate and highlight a weak link in Aristotle's argument, that the blowing of air could suffice to propel the stone. In contrast, Ptolemy used a chain of reasoning that involved Aristotle's theory, computation, and everyday observances.

How Could Space Have a Boundary?

Other questions may be generated by detailed imagining of the consequences of a theory. For example, in the 15th century, Nicholas of Cusa found a contradiction in the traditional world picture of the universe, which consisted of concentric spheres with the earth at the center. According to this world-view, the outermost sphere was believed to be the boundary of both the material universe and space itself. "Yet how could space have a boundary?" he is reported to have asked. "If you stood just inside this boundary and fired an arrow toward it, what was supposed to happen: would the arrow bounce back, or disappear entirely, or what?" (Toulmin & Goodfield, 1961, p. 186).

Rather than passively accepting the current world model, Cusa considered its consequences and tested their plausibility against his own experience of boundaries in the world. Since such boundaries divide regions of space, he would have believed that there is always something on the other side of a boundary. The model of concentric spheres could not account for what would happen when an arrow (for example) encountered the boundary. In Cusa's opinion, therefore, the concept of a boundary to all space was self-contradictory. This illustrates an attitude frequently embodied by scientists' questions — that of open-mindedness, curiosity, or skepticism. This enables them, at times, to question previously accepted answers, or find difficulties in situations that are perceived as non-problematic by others.

How Could the Sun Have Been So Hot Several Million Years Ago?

The following case shows that a contradiction may be identified when the implications of one theory contradict those of an unrelated theory. Physicists of the late 19th century calculated the rate at which the sun was radiating heat. According to the principle of conservation of energy, this implied a corresponding heat loss over time. Their conclusion was that a few million years ago, the sun would have been so hot that the earth could not have supported life. This was not contradictory to daily experience, or other results in classical physics. However, according to Darwin's theory of evolution, natural selection required a longer time scale for the evolution of complex species. This raised the question, "How could the sun have been so hot several million years ago?," which required one of the two theories to give ground. An interesting aspect of this example is that although the problem was identified by comparison to the consequences of an independent theory the difficulty was eventually recognized as internal to physics. Furthermore, although it was originally seen as a minor anomaly, it was one of several such "minor" anomalies that necessitated the revolutionary changes of 20th century physics.[3]

Children's Questions

In this section, I use ideas elaborated in the analysis of questions from the history of science to help understand children's questions and the thinking that underlies them. As above, each of these questions involves the identification of a contradiction. For children as well as for scientists, the questioner is thinking skeptically about a situation that might be taken for granted, and identifying a potential problem.

In common with historical scientists, the children are strongly influenced by their background experiences and beliefs. Consequently, identifying the relevant background beliefs is important for understanding children's questions. It is also valuable to consider the thinking involved. Some of the contradictions are almost self-evident, once the two ideas are juxtaposed. Others seem to involve a multi-step chain of arguments, or detailed imagination of a situation and its consequences.

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[3]The question was never adequately answered by classical physics. The resolution is that by the process of thermonuclear fusion, in which matter is converted to energy, the sun is constantly generating heat. The equivalence of matter and energy is a consequence of the special theory of relativity.

If the Earth Is Tilting, Why Don't We Feel the Tilt?

In the following dialogue, the children articulate two questions that address contradictions between "school learning" (about the earth) and their background experiences and beliefs. In this case, the relevant background influences come from everyday experience. The questions emerged as Dave used a projector and a globe with a stick on the equator to demonstrate the seasonal effect of the earth's tilt on shadows. As he held the earth by the equator, he tilted it back and forth in front of the "sun" to demonstrate the changing direction of its relative tilt during its yearly orbit.

> Dave: It [the shadow] gets longer, shorter, and then starts getting longer again as it goes through different tilts toward that light source there. Yes? [He is calling on Emily.]
> Emily: Well if the earth is tilting why don't we feel it? It's so slow.
> Dave: Um, that's a good question. Why don't we feel tilted?
> Emily: We should feel, like, all of sudden when the earth goes tilting.
> Dave: O.K. I want you to keep something in mind. Our tilt never really changes. We're always tilted toward what, what did we talk about this morning? What are we tilted towards or what is it, our axis draws a straight line to what? We talked about it this morning. Joshua.
> Joshua: The North Star.
> Dave: [Talks about the North Star] Lara, you had your hand up.
> Lara: To what Emily said, "Why don't we feel the tilt?" It's because, as I asked my dad, "The world is round isn't it, so why don't we see the curve?" and he said, "Because it's so big you can't feel it, because it's so big."
> Dave: Yeah that's a good explanation. Because it's so large it's hard to see the roundness of it, right?

Dave's demonstration of changes in the earth's tilt led Emily to ask, "If the earth is tilting, why don't we feel it?" Emily evidently interpreted the changing tilt of Dave's earth model in a literal way, and assumed that "tilt" meant that the earth's axis rocks back and forth. Presumably drawing on her experience of changing tilts in other situations, such as standing on the middle of a seesaw, Emily detected an apparent inconsistency between that visceral experience and the fact that if the earth is tilting, we cannot feel it.

Her identification of this inconsistency resembles the thinking of Philoponos, who found that the Aristotelian idea that disturbances of the air could keep a stone in motion was inconsistent with his experience of throwing stones. It also resembles those who questioned the Pythagorean belief that the movement of the planets produced music, asking why, then, could this music not be heard? In all three cases, the questioners used daily experience in evaluating the validity of a scientific idea or theory. This parallel illustrates one way in which children resemble scientists in their approach to making sense of the world around them. Emily's readiness to articulate the problem she experienced with regard to Dave's lesson also reflects an attitude of skepticism. This tendency to integrate new ideas on the basis of their plausibility and not simply rely on the authority of the sources is often cited as an important scientific attitude.

Dave recognized that Emily's perceived contradiction was based on her interpretation of "tilting" in the context of his model. He sought to clarify the issue and resolve the contradiction by reminding the class that, as they had recently discussed, the tilt of the earth actually remains constant. Therefore, because there is no actual change in the tilt, we should not expect to feel the earth "go tilting." Since Emily did not respond verbally to Dave's explanation, she probably did not find it helpful. However, since the children did not say much, some of the following analysis, which incorporates themes and activities highlighted in the introduction, is speculative.

One potential source of confusion is the ambiguous meaning of the term "tilting" One notion of tilting is a movement in which tilt changes, which could be called "rocking." Another notion is that something can have a fixed state of tilt, which could be called being "angled." Emily's comments that "it's [the tilting] so slow" and that the earth "goes tilting ... all of a sudden" seem to refer to the idea that the earth is rocking, which would follow from a literal interpretation of Dave's model. Dave understood Emily's confusion and addressed it by trying to clarify that the earth is angled toward the North Star, and is not rocking.

The ambiguity discussed above is only one way in which the definition of the term "tilting" is problematic. When used to refer to the angle of the earth's axis, the term, "tilt," is not easily defined and may have been a source of confusion for the children. One reason for this is that in everyday situations there is an obvious vertical direction with respect to which tilt can be defined. A globe makes use of this orientation in depicting the tilt of the earth's axis. However, mapping the local concept of vertical onto the globe quickly leads children to questions that embody contradictions, such as "if people in Australia are upside down, why don't they fall off the earth?" Thus, even an apparently obvious term like "up" (on the earth) has the non-obvious answer: "Up is the direction away from the center of the earth."[4] An adequate definition of the tilt of the earth's axis requires defining a reference direction, such as the normal to the plane of the earth's orbit.[5] Alternatively, the tilt can be defined with respect to the apparent motion of the "fixed stars" and the planets. Thus, although intuitive definitions can be adequate in some situations, they can be a source of perceived contradictions in other circumstances. This example also shows that understanding definitions or constructing them requires more knowledge and experience with phenomena than many educators realize. The process of constructing definitions will be further addressed in the next chapter.

Emily's interpretation of the model also contributed to her perception of a contradiction. Dave's model used a globe, which is a scale model of the earth. Although Emily would not have taken some features of the model literally, such as the colors of the countries, a literal interpretation of the rocking motion was compelling. Dave, however, had constructed the model with the understanding that models emphasize only aspects of the original situation relevant to one's goal, and hence should not always be taken literally. His model "abstracted out" the revolution of the earth around the sun and represented only the radial component of the earth's tilt relative to its orbital plane. However, the children did not appear to understand either the abstractions involved or their justification. It is worth noting that Dave's model incorporated ideas generated by children in a previous year's class, who had spent considerable time grappling with the implications of the earth's tilted axis. It is not surprising that the children in Dave's current class could not make sense

[4]Children's ideas about the earth as a body in space typically do not coincide with contemporary scientific understandings, and have been the subject of numerous investigations (Baxter, 1995; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Nussbaum, 1985; Vosniadou & Brewer, 1992) .

[5]There is a choice between two opposite normal directions. Globes designed from the viewpoint of the Northern Hemisphere portray north as "up." The definition of clockwise is also "north-centric" since it is the direction of movement of a shadow for a sundial in the Northern Hemisphere.

of the model, both because they did not have a role in constructing it and because they did not have much time to interpret it. The construction and interpretation of models will be addressed in more detail in a subsequent chapter.

An interesting aspect of Lara's response is that it can be viewed as relevant or irrelevant depending on one's perspective. According to Dave the core of the perceived contradiction was Emily's belief that the model implied that the tilt of the earth is actually changing. Lara's response indicated that she either did not understand Dave's explanation, or simply ignored it. She introduced a completely different perspective on the situation, connecting a salient feature of the tilting problem, the large size of the earth in comparison to more familiar objects, with a question she had once asked concerning why we don't see the curve of the earth. She implied that the solution of the two problems is similar — because the earth is so large that everyday perceptions do not apply. Since the earth is not actually rocking, this argument is not strictly speaking relevant. However, this explanation would be relevant for the related question "Why don't we feel the earth's rotation?" as well as the question, "If the axis of the earth is at an angle, why don't we feel off balance?," which might follow from a different interpretation of "tilting." Therefore, Lara introduced a valuable object to think with about related phenomena even if it was not relevant to the "scientific" explanation offered by Dan.

Why Do Buildings Have Right Angles and Not Triangles?

"Why do buildings have right angles and not triangles?" asked Mara, after listening to an architect who was invited, as part of a curriculum on "structures," to speak to the class about his work. The contradiction identified by Mara was between her expressed expectation that buildings should have triangles, and her observation that right angles are prevalent. Consideration of her background experience and beliefs will clarify the meaning of her question and the thinking behind it.

In raising this question, she built on learning from earlier structures activities. These included using toothpicks and marshmallows to construct objects, as well as building with other materials such as straws and paper clips. A relevant conclusion that the children reached, after comparing their various constructions, was that structures built with triangles were more stable that those built with squares or rectangles (and hence containing right angles). One contrast between the background influences used to identify the contradictions in these two learning stories is that the expectation of what "tilting" should feel like is based on everyday experience, and is probably implicit, while the understanding about the stability of triangles was based on an intentional learning experience and was an explicit generalization. Similarly, professional scientists are guided by both their intuition about phenomena and by formal theory.

Furthermore, although we cannot know the exact reasoning she used, it would appear to involve more intermediate steps than the reasoning process required to identify the contradictions involving the tilting or curvature of the earth. Recognizing this contradiction required attention to the requirement that buildings be stable, and to two pieces of related knowledge one of which — the stability of geometric shapes — favors triangles over rectangle and the other of which — the appearance of buildings — says this is not so, because rectangles are more prevalent in buildings than are triangles. This learning story also illustrates how apparent contradictions can sometimes be resolved by taking new information into account. As the architect explained to the children, if one looks deeper, houses do contain structures that are triangles — the diagonal cross pieces of the framework form triangles, which can be seen during the early phases of construction.

Two similarities between the thinking involved in this learning story and that frequently present in professional science are the use of theoretical knowledge (i.e., triangles are more stable than rectangles), as well as multi-step reasoning in identifying a contradiction.

Mountains — Why Don't They Fall Down?

A fourth-grade girl raised the question "Mountains, why don't they fall down?" during a brainstorming session on "what, in science, are you curious about?" In this case, the contradiction involved is not immediately apparent. The use of the words, "why don't," however, imply that the child has some reason for assuming that mountains *should* fall down. This leads us to speculate about the background beliefs and experiences that might explain why this girl asked the question. A plausible interpretation of the question is that the girl was comparing mountains to other tall things, such as trees and buildings, which do at times fall down. Although speculative, this interpretation is supported by the fact that hurricanes, which sometimes knock down trees and buildings, had been recently mentioned during the brainstorming session.

In sum, then, considering the possible background influences on the question helps highlight a perceived contradiction. In this case the discrepancy involved the child's recognition that a property of some tall things cannot be generalized to all tall things.

How Did They Get the Video Back from the Moon?

Like the previous questions, this one involved a contradiction that emerged from a discrepancy between background experience and a current situation. Again, a consideration of this experience is necessary to understand the thinking behind the question.

The meaning of the question in the following story was more immediately clear to some of the children in the class than it was to me. This is probably because their prior experience was more similar to that of their classmate than was mine. The setting was a sixth-grade classroom in an affluent Boston suburb, in which children watched a videotape about extremes of temperature on the lunar surface. In the final sequence of the program, the lunar lander was seen separating from its base and flying off to link up with the command module.

As the classroom lights were turned on, one of the boys asked, "How did they get the videotape back from the moon?" I was initially puzzled by his question because I thought of the images as being transmitted through space. The boy, however, was thinking of them as being recorded on a videocassette. This became clear when a classmate, who immediately understood the logic behind his friend's question suggested, "Maybe they sent another moon mission to retrieve it." His comment illuminated the contradiction identified by the first boy, which was based on the assumption that a videocassette showing a lunar lander taking off must have been on the moon at the time. If this was the case, however, the astronauts could not have the videocassette with them when they left.

The question, "How did they get the video back from the moon?" provides an example in which different life experiences play a role parallel to differences in theoretical beliefs. In this case, the difference is between adults who have grown up thinking of television as something that is transmitted, and which comes through the air into an antenna, and children with extensive experience with videocassettes, VCR's, videorecorders, and cable television. The salience of video technology may have been all the stronger because the program they had just viewed was on videocassette. In the case of science history, situations that pose a difficulty for one generation of scientists, who are working within a particular theoretical framework, may not be problematic for their successors, who draw on a different set of beliefs. A Newtonian, for example, would not need to invoke additional forces to explain a thrown stone's continued movement once it leaves someone's hand. Unlike the Aristotelian view, Newtonian theory states that things in motion continue until acted upon by an outside force. Similarly, one who thinks only in terms of videocassettes needs a special explanation for how this cassette was transported, while someone who "believes" in the transmission of signals through space needs no additional explanation. Like scientists, therefore, these children identified a contradiction — and tried to explain it — by drawing on their particular background experiences and beliefs.

There is also a parallel between the boy's thinking and Cusa's thinking with regard to the outermost sphere of the cosmos. In both stories imagining certain details of a situation aided in the identification of a contradiction. To argue with the notion of a physical boundary to the universe, Cusa presented a scene in which one can imagine the course an arrow would take if it encountered a physical boundary. Similarly, the boy who asked about the videotape seems to have been imagining a scenario that included as details the presence of a videocamera with a videocassette on the moon. Although this particular analysis is speculative, this kind of thinking has been a powerful tool for scientists. As previously mentioned, for example, Einstein visualized what would happen if he rode with a beam of light, and ultimately arrived at his theory of special relativity.

"If You Need an Apple Seed to Get an Apple Tree, and an Apple Tree to Get an Apple Seed ..."

The following question showed that an understanding or explanation that is plausible on the surface might be seen on further reflection to contain an inconsistency or contradiction. Ellen, a second grader, asked, "If you need an apple seed to get an apple tree, and a tree to get an apple seed, where did the first tree come from?" She was intrigued by questions of origins, and later asked a similar question: "Who was the mother of the first person?"

If one considers only the ongoing production of apples, the question, "where does an apple tree come from?" has a plausible answer, it grows from apple seeds. A second grader may well have planted and grown some sort of seeds herself, and may also have noticed that apple seeds come from apples. If you have an apple seed, you can plant an apple tree. When you grow the tree, you will produce apples with more seeds and can plant more trees. Many children would be satisfied with this understanding.

However, to Ellen, it was quite clear that this did not explain how the whole process got underway. One piece of evidence supporting this claim is that when I mentioned that many people have been puzzled by similar questions, and that a well known version is "which came first, the chicken or the egg?" she immediately proceeded to work through the analogous logic. "Well, let's see," she pondered, "if you need a chicken to get an egg and an egg to get a chicken, how did it get started?"

Conclusion

This chapter has analyzed children's process of posing questions using as a guide the corresponding practice in scientists. I advanced several arguments as to why this practice should be considered a seed of mature science practice. On a basic level the children and scientists are engaged in the same kind of process. Both are asking questions that identify perceived contradictions as part of their sense-making process, that is, their effort to make coherent sense of the world and their beliefs about it. Looking further, we see that for children, as well as for scientists, this process is shaped by background experiences and beliefs that serve as interpretive frameworks.

Chapter 5: Constructing Definitions

Introduction

In this chapter I explore the process of *constructing definitions* as a seed of science practice, primarily through an analysis of two episodes from the history of science and several learning stories.[1] I argue that the process of constructing definitions deserves attention from educators because it is important to the practice and progress of science, and has received little attention in either school practice, or proposals for science education reform.

One of the episodes from the history of science I use to portray the mature practice of constructing definitions concerns the history of defining *syphilis*. This process was an integral part of efforts to understand and treat the disease, and spanned several hundred years. The other episode concerns the key role played by the operational definition of "sterilization" in a series of experiments testing whether or not spontaneous generation occurs. These stories show how definitions are an integral part of scientific theories, and how they embody an understanding of the world, and inform and constrain scientific exploration. Therefore, like theory-building, constructing definitions is an important part of the nature of science, although it has received little attention from science educators.

In the learning stories children from Dave and Tanya's class construct definitions of terms such as "intelligence" and "shadow," that are important to their own explorations. The stories highlight the children's capacity to grapple with the challenges of constructing definitions, a process many of them find rewarding and engaging.

School Science and Constructing Definitions

Children rarely construct definitions as part of their school science experience. They typically only use ready-made definitions. Such definitions have value because they encapsulate knowledge, and help scientists conceptualize problems, design investigations,

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[1]The process of constructing definitions will also be referred to as *defining terms.*

and communicate with each other. Although ready-made definitions can support children's exploration, use of these products of science without developing an understanding of the process by which definitions are constructed may contribute to a mistaken belief in science as a "ready-made" discipline. For example, if children conduct experiments in which all the definitions are ready-made, they may develop a recipe-like view of experimentation in which all the necessary substances, measurements and tools have been clearly specified; one need only follow the prescribed steps to discover "scientific truth."

Not only is experience constructing definitions absent from most educational practice, but the process has not been an object of serious study for science education researchers. This is true despite their emphasis on the nature of science (AAAS, 1993; Aldridge, 1992; Driver, Leach, Millar, & Scott, 1993). In fact, researchers have not included constructing definitions in their conceptualization of the nature of science. For example, Driver, et al. (1993) present six main categories, containing 25 specific features, that they believe children should know about the nature of science. Although their list contains many more features than they explore in the subsequent research, constructing definitions is not among them. Similarly, the process of constructing definitions is not part of the "nature of science" interview protocol designed by Carey, et al. (1995).

The analysis in this chapter employs all four of the recurring themes introduced earlier: science in the making, background influences, contradictions and groups. For example, as noted previously, the construction of definitions, in contrast to the use of existing definitions, is science in the making. The role that background influences such as a belief in astrology, and ideas about olfactory neurons play in both the scientists' and children's construction of definitions will be seen in the stories in the chapter. Several stories also show how definitions are modified in the face of contradictions or counterexamples. As will be seen, group process often contributes to the identification of these contradictions.

In summary, this chapter is an analysis of the children's process of constructing definitions, a seed of science practice that has received insufficient attention from science educators.

Themes to Be Explored

The broadest theme of this chapter involves *the dynamic relationship between constructing definitions and the rest of science exploration.* Episodes from the history of science and learning stories from the classroom are used to illustrate the iterative process through which the construction of working definitions impacts on the process of exploration; exploration in turn, fosters the revision of definitions.

The chapter will emphasize two key features of the process of constructing definitions. The first is *establishing the scope of a term*, or determining which things it will include, and which it will exclude. At times, for example, a definition may be overly inclusive because the topic of interest is conflated with other, similar phenomena. As will be discussed below, the initial definition of syphilis conflated the disease we now identify as syphilis with gonorrhea and other venereal diseases. Conversely, differences such as those of appearance or location between phenomena can lead to the mistaken assumption that they are unrelated entities. One who has not observed the metamorphosis of caterpillars into butterflies, for example, might assume that they are two unrelated creatures.

The process of constructing definitions is a part of theory construction. Just as observation is viewed by most philosophers of science as theory-laden (Hanson, 1958), definitions are also theory-laden. This means that items that were in the scope of distinct terms under one theory may be in the scope of a single term according to another. For example, as noted in the previous chapter, Aristotle divided motions into *natural motions*, such as the orbiting of the moon, and *forced motions,* such as the movement of a thrown apple. Newtonian physics, however, explained all motion in terms of forces. This erased Aristotle's distinction and replaced it with a single term — *motion* — that included the phenomena that had previously fallen into the scope of two terms.

An additional example of the connection between theories and the scope of terms follows from viewing apples and the moon in the context of theories of matter. Aristotle held that terrestrial objects, such as apples, were mutable and composed of four elements (earth, air, fire, and water). In contrast, celestial objects, such as the moon and the stars, were eternal and therefore made of a special fifth element — the quintessence. Modern atomic theory makes no comparable distinction; the elements that comprise the stars are the same as those that make up matter on earth . In short, with the advent of modern atomic theory only one term — *matter* — was needed to describe and explain the properties of what were once considered two fundamentally different kinds of matter. The second major aspect of constructing definitions to be addressed in the chapter is *the process by which definitions are made "operational,"* so that they can be measured and manipulated. Although intelligence is a contentious and elusive concept, for example, many researchers have operationalized it by administrating IQ tests, which provide a quantitative measure susceptible to statistical analysis. Similarly, those who study infant experience have operationalized attention by measuring the rate at which babies suck, the rate and direction of their eye movements, and their heart rates (Bower, 1982).

The presence of *confounding factors* can make the processes of operationalizing or establishing the scope of terms more difficult. *Confounding factors* are factors separate from the term being defined that nevertheless influence the results. The emphasis in this chapter will be on confounds that are closely linked to the phenomenon being defined, rather than those which are more generally a matter of experimental technique. As will be discussed below, for example, for many years efforts to define the disease we now know as syphilis were confounded by its similarity to other diseases that cause genital symptoms.

Episodes from the History of Science

I use the episodes from the history of science that follow to help articulate the meaning of the concept *constructing definitions*, and to illustrate its role in the practice and progress of science. One focus of the section is factors that influence the construction of definitions, such as experience, beliefs and the impact of counterexamples. These episodes show how the iterative development of definitions can be an integral part of the scientific inquiry process. In the subsequent section, I will use these stories as reference points to analyze the children's process of constructing definitions as part of an investigation.

Delimiting the Scope of the Definition: The Case of Syphilis

The History of Defining Syphilis

Because the definition of syphilis developed over a 400 year period, it presents a clear example of the iterative cycle of constructing definitions, employing the definitions in scientific exploration, and changing the definition as a consequence of one's findings. As will be illustrated by the following episode, which was taken from Fleck's (1979) analysis of the history of syphilis, a key feature of this definition process involved successive refinements in the scope of the term. The process was also influenced by the cultural and theoretical beliefs (background knowledge) of the investigators. Again, because the definition emerged over four centuries, changes in these beliefs were particularly dramatic and influential.

In the late 15th century, the disease we now call syphilis was conflated with other venereal diseases, such as those now classified as gonorrhea, soft chancre, and lymphogranuloma inguinale.[2] At that time, astrology played an important role in both a scientific and everyday understanding of the world. According to this world view, the genitals were ruled by the sign of Scorpio. The conjunction of Saturn and Jupiter, under the sign of Scorpio and the house of Mars, on November 25, 1484, was believed to have caused the outbreak of syphilis that occurred in the late 1400's. Religious leaders also added to the stigma of syphilis by teaching that the disease was a punishment for sinful lust. By over-emphasizing the role of sex and genitals, 15th century thinkers were led to

[2]As early as 1503, syphilis was known in English as the "Great pox," the "French pox," or the "Spanish pox." The word, "syphilis," which entered the English language in 1718, comes from the title of a poem, "Syphilis Sive Morbis Gallicus," written in 1530 by Girolamo Fracastoro. The disease is named after the hero of the poem, Syphilus, a shepherd and the first person to suffer from the disease.

view syphilis and all other venereal diseases as one illness. This was also the reason that congenital syphilis, as well as the secondary and tertiary stages of the disease, which are not characterized by genital symptoms, were not recognized as manifestations of syphilis.

The next characterization of syphilis was based on the discoveries of medical practitioners, who observed that syphilis, unlike other venereal diseases, responded to treatment with mercury ointment. The new definition, an operational one, was "the disease that responds to mercury treatment." Although this did not overturn earlier views of the disease, it led to the coexistence of two views. One conceptualization emphasized the role of sin and the stars in creating a "carnal scourge." The other was based on empirical observation and the disease's response to treatment.

Later, the definition of syphilis was influenced by attempts to identify specific characteristics of the blood of people afflicted with syphilis. The earliest efforts reflected the contemporary belief in the significance of the four humours and attributed symptoms to qualities such as "melancholic blood." By the late 19th century, numerous biological and chemical analyses had been conducted in an effort to identify differences between the blood of syphilitics and that of healthy individuals. However, no analysis produced diagnostically useful results until the discovery of a complex serological test called the "Wassermann reaction." This test made it possible to identify syphilis in the secondary and tertiary stages of the disease. It ultimately led to our current understanding of syphilis as a three-stage venereal disease that is caused by a microorganism (*Spirochaete pallida)*, and which is usually transmitted by sexual intercourse, or acquired congenitally.

Analysis of Defining Syphilis

The main theme illustrated by this episode is the process of delimiting the scope of a term. Initially, what are now seen as several venereal diseases were referred to by the single term "syphilis." Over time, subsequent definitions differentiated syphilis from gonorrhea, soft chancre, and other sexually transmitted illnesses. In addition to being too inclusive, the scope of the term was initially too narrow, and was later broadened to include advanced and congenital forms of the disease. These changes in scope corresponded to empirical discoveries, changes in prevailing belief systems, and an improved understanding of the disease and its treatment.

The close connection between belief systems and constructing definitions is illustrated by the significant role astrology and the belief in "carnal sin" played in this process. Both belief systems led investigators to overemphasize the role of genitals. By viewing syphilis as a punishment for unsanctioned sexual activity, or a consequence of stellar activity, all genital symptoms were easily assumed to be manifestations of the same illness. Similarly, because the disease was linked *only* to sexual activity, there was no reason to believe that infants might have the disease, or that the symptoms of advanced syphilis might be non-genital. From the perspective of modern science, some would say that early investigators made "errors of inclusion and exclusion." However, an historically-based analysis shows that the early definitions were firmly rooted in the beliefs of the time.

This episode from the history of science also illustrates the iterative inter-relationship between definitions and the rest of the exploration process. The early, genitally-based definition fostered investigations which focused on genital symptoms and their treatment. Later, the experimental discovery that some genital symptoms were alleviated by mercury led some investigators to re-define syphilis in terms of its response to this treatment. In turn, this differential diagnosis motivated a search for blood-based indicators of the disease, which eventually led to the "Wassermann reaction," and the discovery of the role of *Spirochaete pallida*, resulting in our current definition of syphilis. This iterative process can also be viewed as an interplay between conceptual definitions (such as the definitions of syphilis as a "carnal scourge," or as a "disease entity associated with a microorganism") and operational definitions (e.g. in terms of treatment or diagnosis).

In sum, the story of defining syphilis shows how the scope of a term can evolve over time. It can be refined both by excluding phenomena that were initially conflated with the term, as well as by including some that were originally seen to be independent. This refinement involved interplay between operational and conceptual definitions. Because the process unfolded over a period of four centuries, its iterative nature, and the role played by changing beliefs and theories, are especially evident.

Operational Definitions: The Debate over Spontaneous Generation

The Debate

This episode from the history of science emphasizes the process of constructing operational definitions, and its impact on scientific exploration. The subject is a series of experiments that explored "spontaneous generation," the notion that life can spring from non-living matter in a short period of time. The key construct that needed to be operationalized was sterilization. As the story will show, despite the efforts of two leading scientists, a flaw in the operational definition of sterilization remained obscure until decades after the experiments were conducted.

During the 1860's in France, the debate over spontaneous generation culminated in a series of competitive experiments conducted by Louis Pasteur and Felix Pouchet (Collins & Pinch, 1993). A proponent of spontaneous generation, Pouchet believed that new life could arise in a matter of minutes or hours from a sterilized medium. In contrast, Pasteur claimed that what seemed to be the rapid generation of life from inorganic matter was, in fact, the work of microorganisms.

The standard experiments were, in principle, simple. To create a "sterile medium," any existing life was destroyed by boiling the organic matter in a flask. When the steam had driven out the air, the flask was sealed. It was then reasoned that if the admission of sterile air into the flask was followed by the appearance of life, such as mold, spontaneous generation had occurred.

The debate pivoted around the contentious issue of finding an adequate operational definition for sterilization. Had there been available direct methods of evaluating whether a medium had been sterilized, sterilization procedures could have been evaluated independently from experiments such as these. However, with the microscopes of that time, no one succeeded in determining whether the sterilization procedures actually destroyed all forms of life. The result of any particular experiment, therefore, could be questioned on the grounds of inadequate technique. Should mold grow, opponents of spontaneous generation could claim that either the organic material was not sterile, or that the air was contaminated. Conversely, should life fail to appear, a proponent of spontaneous generation might claim that the nutritive value of the growth medium had been destroyed by the sterilization process. Many sterilization procedures, such as the use of various caustic chemicals, were investigated, yet for a long time there was no agreement as to their effectiveness.

By the time of the Pasteur-Pouchet debate, boiling was accepted by both sides as an adequate means of sterilizing the growth medium. In other words, boiling had become the "operational definition" of sterilizing a growth medium. The key experimental challenge, therefore, was perceived to be the sterilization procedures for air. Pasteur conducted his crucial experiments in the pure glacial air of the French Alps using a growth medium of yeast. To prevent contamination when air was admitted to a swan-necked flask, he used a long, heated pair of pincers to snip open the narrow neck and immediately re-sealed it. Life developed in only one of his 20 flasks. However, when Pouchet replicated Pasteur's experiment, all six of his flasks developed life. Because he opened his flasks with a heated file instead of pincers, opponents of spontaneous generation argued that small particles of glass may have been a vector for contamination. Pouchet abandoned his claims and experiments, and most 19th century scientists concluded that inadequate procedures for maintaining the sterilization of air in the flasks accounted for demonstrations of "spontaneous generation."

Many years later, investigators made a discovery that overturned the previously accepted explanation for the divergent results of the pivotal Alpine experiments. Both sides in the debate had agreed on boiling in water as an operational definition of sterilization. It was therefore considered inconsequential that Pouchet used a hay infusion instead of yeast as his growth medium. However, it was subsequently shown that hay infusions frequently contain a spore that cannot be killed by boiling in water at atmospheric pressure. The accepted operational definition, therefore, proved inadequate. Because the limitations of boiling in water were unknown, the experiments were confounded by the use of hay instead of yeast.

Analysis of the Debate over Spontaneous Generation

This complex story illustrates some of the challenges of creating valid operational definitions and identifying confounding factors. First, it provides an example of how an accepted operational definition, that of the sterilization of solid organic matter, proved to be inadequate, with consequences for the interpretation of crucial experiments. The question of whether spontaneous generation occurs reached the same conclusion we draw today, but only through a misinterpretation of what caused mold to grow in Pouchet's flasks. This double misinterpretation (that boiling sterilized the hay infusion, and that particles created by the file led to contamination) highlights the value of being able to validate an operational definition independently from an experiment in which it plays a crucial role. In this case, there was no way to judge whether a medium was, in fact, sterilized, other than whether it supported the growth of life. As noted previously, this often resulted in circular arguments about the validity of experimental procedures and outcomes. The development of more powerful microscopes made it possible to detect smaller life forms directly.

Beliefs and theories played a somewhat different role in this episode than they did in the story of defining syphilis. This is because the two protagonists in the debate shared a very similar set of beliefs about experimentation, and held many biological theories in common. Although they disagreed about spontaneous generation, they both looked to biology, and not astrology or religion as the appropriate framework for explanation. On the other hand, this episode is a case in which scientists' differing biological beliefs strongly influenced the position they took in a controversy. Pouchet was a believer in Darwinian evolution. For him spontaneous generation was necessary to support Darwin's then highly controversial theory. Pasteur, on the other hand, did not disagree with Darwin's theory, but had his own agenda to promote: demonstrating the role of microorganisms in disease and biological phenomena.

The Way School Textbooks Represent the Story of Spontaneous Generation

In contrast to the complexity of the story presented above, school textbooks typically ignore the problem of defining sterilization, and simply state what Pasteur did and what his experiments showed. For example, a middle school textbook called *Life Science: The Challenge of Discovery* (Warner, Lawson, Bierer, & Cohen, 1991), published by D.C. Heath and Company, explains Pasteur's role in the debate over spontaneous generation as follows:

> A little more than a century ago, a Frenchman named Louis Pasteur settled the argument over spontaneous generation. Pasteur's experiment is shown in Figure 2-21. With this experiment, Pasteur proved that tiny organisms did not come from nonliving liquids. The belief in spontaneous generation was finally proved wrong (Warner, et al., 1991, p. 52).

"Figure 2-21" is a picture diagram of three flasks. The caption under the first flask (which is sitting on top of a heat source) says, "Broth boiled for 1 hour." The second caption is "No microscopic organisms develop" and the third is "curved neck broken; organisms develop." A short description to the left of the diagram reads:

> Pasteur's flasks let in air but kept out dust, which carries microscopic organisms. His experiment proved that microscopic organisms do not develop from broth (Warner et al., p. 52).

A similar description is included in a textbook published by the Addison-Wesley Publishing Company. In this textbook, the authors describe the long-necked flasks used by Pasteur, which allowed in air but blocked dust. They conclude their brief description by stating that "Pasteur had shown that organisms could not appear in the soup unless the soup first came in contact with living organisms. Since the results of this experiment became known, scientists have not believed in spontaneous generation" (Barr & Leyden, 1986, p. 29). Textbooks by other well-known publishers, such as Macmillan (Jantzen and Michel, 1986) and Glencoe (Aldridge, et al., 1995) offered no more details.

These accounts remove most traces of science in the making from the story. Both books describe the experiments of Spallanzani, an Italian scientist who lived a century before Pasteur. However, only the second book explicitly links his work to Pasteur's. Both books omit the contributions Pasteur's contemporaries made to the development of the experimental and theoretical frameworks that informed his work. Neither book addresses the intellectual and the practical difficulties of establishing a shared and operationalized definition of the key concept of *sterilization.* Students are simply told that Pasteur boiled the broth and that he used special flasks that kept out dust. Furthermore, both books incorrectly state that a single experiment vanquished belief in spontaneous generation. They make no note of the controversy surrounding Pasteur's work. These textbooks do not include the messy details of science in the making involved in the debate over spontaneous generation. In particular, the challenges of finding satisfactory operational definitions of sterilization for both the growth medium and for the air is not addressed at all.

The preceding analysis of an episode of from the history of science partially unpacked the role of the definition process in experimentation. In a subsequent analysis of two girls' experimental search for gender differences in the sense of smell parallels with the story of spontaneous generation will be developed.

Learning Stories

Children involved in genuine science exploration must, like professional scientists, sometimes define their terms. The analysis of the following learning stories identifies seeds of science practice in the children's process of constructing definitions. The challenges they face, the processes they undertake, and the role played by background influences are similar to those of professional scientists. This similarity will be most evident when the children become involved in a process of argument and counterargument that stimulates them to propose counterexamples and consider alternative ideas.

This chapter presents and explore four learning stories, using each to discuss aspects of the children's reasoning.

In the first learning story presented in this chapter, the children became thoroughly engaged in defining the term, *intelligence*. As in the story of syphilis, their definition process was influenced by their experience and beliefs. The context of the definition process was the exploration of the question "Is there intelligent life elsewhere in the universe?"

The second learning story describes a whole class effort to define shadows. While the construct of intelligence is so broad, complex, and controversial that it continues to elude definition (Gould, 1981), shadows are accessible to observation, experimentation, and definition. The story shows the children making use of relevant experience in reasoning about a definition. It further illustrates their ability to use a special case to re-evaluate a previously satisfactory definition.

As children pursue their own interests by designing original experiments, they must also grapple with operational definitions and confounding factors. I use two stories to explore these themes. A brief description of a pet race, designed by two girls for a school science fair, illustrates a lesson they learned when their experiment was undermined by an unexpected confounding factor.

A series of "smell experiments" conducted by two girls is the most extensive children's exploration analyzed in this chapter. As the children tried to prove that "girls smell better than boys," they became engaged in an iterative process of definition, experiment, and analysis. They used their experience and theoretical beliefs as guides that helped them progressively delimit the scope of the term, "sense of smell."

Intelligence: Steps Toward Constructing a Definition

The following learning story describes four children's attempt to define intelligence. The presentation of their discussion aims to capture its richness. The analysis highlights features that were introduced in the analysis of the episodes from the history of science, and were present in the children's definition process. These include: the role played by their experience and beliefs, delimiting the scope of a term, and operationalizing a definition. The dynamics of argument, counterargument, and the use of contradictions and special cases as "objects to think with," which were introduced in the previous chapter and which play an important role in professional science, will be shown to drive the definition process. This process provoked their thinking about intelligence, but did not lead to agreement on an articulated definition.

The topic of intelligence arose as they explored the question, "Is there intelligent life elsewhere in the universe?" In a previous session, the group had considered several methods through which they might find intelligent life, such as the use of probes and human expeditions to other planets. As this session began, Brad, the only boy in the group, commented that in looking for intelligent life, they would have to "look for things that move." "If they don't move," he stated, "they can't be intelligent." This led to a disagreement between Emily and Brad on the connections between intelligence, life, and movement. Sally, frustrated with the interchange, commented that, "we don't *know* what intelligent life is." Her point sparked a lively, 45-minute discussion, in which the children tried to define intelligence.

The Exploration of "What Intelligent Life Is"

As the discussion began, Brad stated that "it is some kind of intelligence to have life." Although his point was not initially well received by the others, this view, as well as the issue of whether or not something must be alive in order to be intelligent, frequently re-emerged during the discussion.

The conversation quickly turned away from whether being alive was a sufficient condition for intelligence, and the children began to draw on several commonly held beliefs in their effort to define the term. Brad, for example, stated that intelligence is "getting a 100 on your I.Q. test." Sally argued that although I.Q. tests might be an acceptable measure of human intelligence they might be inadequate for evaluating life on other planets. "How are we supposed to know if there is intelligent life," she asked, "because we can't, you know, give them an I.Q. test, like 'what is 2 + 2'?"

Sally's view that the belief that intelligence is comprised of knowledge, such as the ability to compute "2 + 2," was again reflected in her proposed counterexample to the belief that something must be alive in order for it to be intelligent. "This," she claimed, holding up a volume of an encyclopedia, "is an intelligent thing, but it's not necessarily alive." Her peers, however, were not convinced. "I don't think so." "No." "It has intelligent writing *in* it, but it, itself, is *not* intelligent, no."

Lara countered Sally's provocative claim by making a distinction between something that has intelligent content (e.g., a book) and something that is, itself, intelligent (e.g., a person). She then formulated her own explanation of what intelligence is. "Like when you understand something — anything — and you're able to take it and sort it out in your head, understand what it is." Lara had broadened the scope of the discussion by conceptualizing intelligence as problem-solving ability, rather than the possession of knowledge.

Emily, introduced a different perspective on the view that intelligence primarily involves a store of information. "Well, she said, "people say that computers are intelligent, but they're not intelligent because people programmed them ... See, the only reason they're intelligent is that ... when you program them you're teaching it all this information."

Lara countered Emily's point by returning to the theme of problem-solving and understanding, which to her were key elements of intelligence. In her view, computers *are* intelligent, because they are capable of actions that indicate understanding.

> Lara: But see I think [computers] are intelligent because ... most computers have certain codes that if you type in... And you can program it to, like ... you can say 'computer do 2+2' and then it will say four ...
>
> Aaron: Wait, you mean verbally or type in?
>
> Lara: If you type in. But if you say 2 or 4 or 2, and you program it 2+2, the computer will take a minute, take in what you have typed, understand it and then put out.
>
> Emily: But a human being programmed it, O.K.? Because human beings also have to know 2+2 presumably.

When Emily stuck to her position (computers are programmed and hence not intelligent), Lara tried another tack. She argued that humans are not so different from computers in possessing and using knowledge from other sources.

> Lara: But if you're saying that humans are intelligent, but most of the stuff that you know somebody else has taught you and so that means that they -
> Emily: It's been passed down from generation to generation.
> Lara: No, they are programming you to think that, and know that, and be able to use it.
> Emily: So in other words we're stupid. We're born with nothing and then programmed.
> Lara: If we're intelligent, then the computers are.

Emily, however, could not be convinced that humans, too, are programmed, and she went on to cite the human capacity for memory to support her case.

> Emily: Now if you can remember, then that's thinking for yourself in some ways, well sort of. If I keep telling you this stuff and you remember when you're 85 years old, then that's not just me programming you, I mean it's partly me programming you ...
> Lara: You're telling them to remember stuff.
> Sally: But –
> Brad: Listen, listen. If you program the computer to do something, unless you erase it then it'll keep on going for hundreds of years.

Emily was implying that even if humans are, to some extent, programmed, their ability to remember what they are taught takes them beyond simple programming. However, Brad disagreed, and pointed out that computers can store information for far longer than humans.

I introduced another example, which I hoped would sharpen the debate about the relationship between computers, life, and intelligence: Data, an android from the television program *Star Trek: The Next Generation*.[3]

> Aaron: O.K. supposing there actually were a being like Data, that is, an android -
> Brad: Cool!
> Emily: Yeah, he's intelligent.
> Aaron: Would you imagine then, first of all, would you say that Data is alive?
> Brad: No.
> Aaron: Would you say that Data is intelligent?
> Brad: Yes.
> Aaron: O.K..
> Emily: O.K., that's completely contradictory to before.
> Sally: But that's because he can think for himself.
> Aaron: O.K., so you think it's thinking.
> Lara: But you don't know, was Data programmed by someone?
> Emily: Yes.

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[3]In the context of the program, Data is both a machine and intelligent. Data would like to be as human as possible, and some episodes use his character to explore themes about human nature.

Brad: Yes.
Lara: Then he's not intelligent.

The example of Data motivated the children to explore one aspect of their discussion further — can a computational object be intelligent, even though it is not alive? To draw out their thinking on how beings might be recognized as intelligent when they cannot be given standard measures of human intelligence (a point made earlier by Sally), I introduced a second example, dolphins.

> Aaron: ... do you agree Sally, that they're intelligent? So why do you say that dolphins are intelligent?
> Sally: Because they have bigger brains than we do.
> Lara: No, they might not know the signing of the Declaration of Independence.
> Emily: They're not supposed to.
> Aaron: O.K., so you think the size [of their brains) is important. I mean elephants probably have bigger brains than we do.
> Brad: They don't.
> Emily: Um we just know by human instinct.
> Lara: Because they can think for themselves and they can learn.
> Aaron: Wait, O.K. how would we know if they can think because we can't see them thinking.
> Emily: Oh you want to find that out, look in a marine encyclopedia.

All of the children held a prior belief that dolphins are intelligent. Because I wanted them to generate their own way of evaluating dolphin intelligence, I reframed the question.

> Aaron: Suppose you didn't know about dolphins O.K.? And then you encountered dolphins and you wanted to find out if they're intelligent. [What would you do?]

After Emily argued that some dolphin behavior might reflect simple learning rather than true intelligence, Lara turned the focus to dolphins' natural behavior.

> Lara: No, but think about it. If you watch a dolphin in its natural habitat ...
> Aaron: O.K..
> Lara: For a long time it will try not to get attacked. But to eat, it might get caught in a fisher net or something like that ... and they will try to get out of there, wiggle themselves away, something like that, so that means they are aware of what is going on, it means they are thinking.
> Aaron: O.K. so you would look at particular behavior like trying to get away.
> Brad: I agree.
> Emily: Oh.

Rather than trying to administer a test to it, or try to teach it something, Lara argued, one should observe it in its natural habitat, and look for evidence of behavior that may manifest underlying thinking.

Since even simple animals might exhibit some form of self-protective behavior, I asked if all animals were intelligent.

Emily: No animals aren't as intelligent as humans.
Brad: They are intelligent. They can think.
Emily: Yeah, they're pretty intelligent.
Sally: I'd say they're like about as intelligent as man was a few hundred years ago. And maybe now we don't know what they think.

Emily, Brad, and Sally all used human intelligence as a yardstick and decided that animals are intelligent, but not as intelligent as humans. When Emily wondered whether one could determine if an ant is intelligent by observing it in its natural habitat, Brad stated, "it collects food and it eats. I think that anything that eats is alive" (because the focus of the discussion was on intelligence, it seems likely that he also meant that ants are therefore "intelligent").

Brad's comment brought the dialogue full circle, echoing his earlier statement that "it is some kind of intelligence to have life."

Analysis of the Exploration of "What Intelligent Life Is"

The preceding narrative has shown the texture and nuance of the children's process of defining the term, "intelligence." The following analysis focuses on several aspects of this definition process, including 1) the role of background experience and beliefs; 2) using special cases as "objects to think with"; and 3) the role of argument and counterargument in driving the definition process.

The Role of Experience and Beliefs

The children's ideas about intelligence were informed by ideas common in the popular culture, and by their own experience. For example, some of the ideas they expressed early in the discussion, such as the association between intelligence and I.Q. tests, and the belief that it involves computational skill (2 + 2) and the possession of knowledge, are beliefs that are common currency in our culture, as was the belief in astrology at the time syphilis first appeared. These beliefs may also have been reinforced by their own test-taking experience.

Personal experience also proved to be a useful tool for raising and resolving questions about intelligence. These children all had experience with computers, and referred to them in their efforts to define intelligence. They all saw parallels, albeit different ones, between humans and computers. On the behavioral level, they recognized that computers can match and exceed human computational abilities. Comparisons between the inner workings of computers and humans were also made, as the children discussed memory and programming.4 This will be discussed further in the following section on special cases as "objects to think with."

Special Cases as "Objects to Think With"

Special cases, such as computers, Data, or dolphins, can serve as "objects to think with" (Papert, 1980). Interestingly, when the children used their understanding of computers and programming to explore their ideas about intelligence, their discussion addressed a questions that continues to generate debate among professionals interested in Artificial Intelligence (AI) — are computers capable of intelligence? If so, what would it mean for a computer, or a computer program, to be intelligent?

Although the arguments and positions of the girls are less sophisticated than those of the professional supporters and critics of AI, their stances resonate with a basic divide in the field. For example, Emily's claim that computers are "not intelligent because people programmed them" has something in common with John Searle's argument that performances that simply involve syntactic operations, such as those exemplified by computer programs, are not a sign of understanding (Searle, 1980).

In contrast, Lara argued that computers are intelligent, because they are capable of intelligent *performances*, such as "adding two and two" (this addition problem was Sally's example of an IQ test question). Although her example is much simpler than the "Turing

[4]It is also of interest to note that the children's comfort with the comparison between computers and humans is culturally based. Although at times they wanted to maintain distinctions between humans and computers, they were comfortable speaking of the two in the same breath. This reflects the enormous change in intellectual climate that has taken place since 1747, when Julien de la Mettrie published his essay, L'homme Machine. In this essay, he claimed that mechanical explanations could, in principle, account for all human activity, including thinking. At the time, the angry reaction to these ideas forced him to seek safety in Berlin, where Frederick the Great was a patron of free thinkers.

Test" (Turing, 1963), she is arguing that surface behavior is sufficient criteria for intelligence.

After Emily rejected this viewpoint, stating that computers only have this ability because they are programmed by humans, Lara argued that humans are also programmed, so being programmed cannot preclude intelligence. Here, she has echoed the agenda of some cognitive scientists, who attempt to understand human thinking by comparing the brain to computers.

Objects to think with can also take the form of special cases, such as those which push the boundaries of a term being defined. These cases can help scientists and children develop criteria that refine the scope of a term. For example, the children used the case of "dolphins" to identify purposeful, problem-solving behavior as a criterion for intelligence. In doing this, they extended their definition of intelligence from measures associated with human intelligence (i.e., IQ tests, computational skills, and the possession of knowledge) to criteria applicable to a broader domain, which included animals (and possibly aliens).

The children also used an object to think with to balance the relative importance of two criteria. When Brad decided that Data is intelligent despite the fact that he is not alive, he abandoned (albeit temporarily) his earlier claim that something must be alive to be intelligent. Data, as an "object to think with" confronted Brad with a contradiction in his beliefs. His choice showed that at that moment, Brad considered the ability to think a stronger criterion for intelligence than being alive.

The Role of Argument and Counterargument in Driving the Definition Process

The preceding section showed how objects to think with can challenge children to refine their thinking with regard to a definition. The discussion of computers also illustrated the way in which children are stimulated to revise their ideas in response to the critique of others. As they tried to decide which things were intelligent and why, the children engaged one another in an on-going debate, which led them to introduce and defend alternative views of intelligence, and illustrate these views with examples and counterexamples. As a result, their collective thinking more closely resembled that of scientists than might have emerged if each child had explored the topic individually.

For example, when Brad stated that intelligence is "getting a 100 on your I.Q. test," Sally pointed out that this specifically human measure of intelligence might not be adequate for evaluating life on other planets. This broadened the group discussion to include the very important methodological question of how nonhuman intelligence might be measured. Similarly, when Sally used the case of an encyclopedia to counter Brad's statement that life, itself, constitutes intelligence, she stimulated the group to differentiate between *being* intelligent and containing "intelligent" material.

Group debates also give children new ideas with which to support their arguments. For example, early in the conversation, Sally claimed that containing knowledge was evidence of intelligence. However, Lara disagreed and stated that intelligence was the ability to "sort [something] out in your head, understand what it is." Sally later adopted Lara's viewpoint herself to argue against Lara that computers are not intelligent. "To be intelligent," Sally said, "means you can think for yourself ... Computers can't think. They do what you tell them to ... Therefore, they can't be intelligent."

In sum, then, the children's discussion of intelligence provides a rich narrative that reflects several aspects of the process of constructing definitions in science. These include the role of experience and beliefs and the thinking sparked by objects to think with. This process generated a number of ideas that helped the children delimit the scope of the term, "intelligence." These included drawing a distinction between containing intelligent information (as is the case with an encyclopedia) and being intelligent; seeing intelligence as the ability to understand new things, and recognizing as intelligent a being's purposeful, problem-solving behavior in its natural environment. Some issues remained controversial, such as whether being alive was a necessary or sufficient criterion for intelligence, and whether intelligence could be programmed into a computer. Thus, although the exploration did not result in a complete or explicit definition of intelligence, the children did think productively about what it might (and might not) be.

The analysis also addressed the way in which arguments and counterarguments lead children to generate and revise ideas, consider alternative viewpoints, and use new ideas to support their thinking. In so doing, their collective process is more like that of scientists than is likely to be the case when children explore ideas on their own.

What Is a Shadow?

This story highlights the role of experience, belief and special cases in shaping children's definition process. This group effort to answer the question, "what is a shadow?" took place late on a Friday afternoon. The class had gathered together to continue their exploration of the relationship between shadow length and the location of the sun in the sky. Many children were restless, and, several looked out the window and shouted, "It's snowing!" "Whoa!" "Oh my God!" Oh wow!" "It's snowing!" In order to bring the children's attention back to the realm of shadows, Dave changed his agenda, and presented the group with a question that one of the children had posted on a computer bulletin board. "Here's a question that may sound simple," he began, "but," he continued, "I want you to think about it before you answer. 'What is a shadow?' I want everyone to give that question a little bit of thought, and then I'll call some people." Dave's agenda, to have the children to define the term, "shadow," quickly brought the class to life.

"It's blocked light," said Larry, who was not usually excited by the science lessons. "I say it *might* be true," said Sally, who had a passion for disagreeing with her classmates, "but it could be just the presence of light and... *that* sounds more like the absence of light ..." "*I* agree with Larry, stated Lara, coming to the first student's defense. "There's light, but there's something in the way, so it's being shut off." Children who rarely participated in science discussions jumped in.

> Eduardo: You know how you say it's blocked light, but then how would it make a shadow if the sun's like this, coming down all around?

Francoise: Because there's light around it and you see it, but it's just that in that particular place there is no light because you're seeing blocked light or something.
Dave: Does that make sense to you?
Eduardo: No, I see what she's saying, that there's light all around, and if you're standing in one place where the sun can't hit, so, you're making a shadow.

Jenna tried to clear up the confusion with a demonstration and explanation.

Jenna: Steve and Larry said, like, it's the absence and presence of light. I agree with both in that it's like, the light is there, it's like ... if this pen wasn't in the center of the table, then that table would be, like, full of light. But, because the pen was there, because I put it there ... there's one part of the table that doesn't have light. Because of the pen and you were shining the light at the pen, at one side of the pen so, there was a blockage of light on the other side of the pen, directly parallel of the light. And so ... the light is there, but its not on that particular spot.

In carefully describing the situation, Jenna identified two attributes of shadows that had not yet been addressed. She noted that shadows are formed on a surface (the table) that would be "full of light" if not for the presence of a blocking object. Furthermore, she observed that the location of the shadow is determined by the direction from which the light originates. However, other children did not respond to these features of her explanation. Thus despite the contribution of several children to articulating additional features of shadows, the initial definition, "blocked light" held center stage.

When the discussion turned to the question, "what are shadows made of?" Jenna tried again to articulate her thinking.

Jenna: Because a shadow, is ... just like a blockage of light, but ... it is a shadow because there's something blocking the light. There's light and there's a surface that the shadow's on, and that create it, but I don't really think that a shadow is part of it ... I mean, a shadow is just, where there's no light on that spot, or, I mean, that could be what a shadow is, and so, when there's no light, like at night, when there's no moon and, then, and um, would that be like a shadow? ... It's the same thing as if, um, there was like a table blocking out the sun. Then, the whole world would be shadowed. And so ...um ... I don't think it's really made of anything, but there are things that are needed to be to create a shadow, like a pen, a surface, and, and some source of light.
Dave: A pen?
Jenna: A pen. I mean, like an object.

Once again, Jenna has emphasized the important role of surfaces in the creation of a shadow. Although she did not think a shadow is "made of anything," she identified three things that are required for the creation of a shadow: an object, a surface, and a light source.

Larry's initial terse description, "blocked light," aroused some controversy, but after a period of exploration, it was generally accepted as a valid encapsulation of what a shadow is. However, consideration of another special case revealed an ambiguity in this definition.

The controversy was started by Sally who wondered whether nighttime is a shadow. Some children thought so. Others disagreed, and for some children the question didn't even make sense. In response to this confusion Sally restated the issue: "It's sort of like, like it could be we're turned away from the sun and that's our shadow and all that. And like if we rotate and um, we create a shadow?"

At this point, Dave suggested that Larry's definition might help resolve the question.

> Dave: Well, let's go back to Larry's definition of what a shadow is.
> Student: Blocked light
> Dave: Is nighttime blocked light?

Most children were led by this logic to agree that nighttime should be considered a shadow. The application of Larry's definition implied that because nighttime is due to the blockage of the sun's light by the earth , it is a shadow. However, Lara, who initially approved of Larry's definition, found that this implication violated her intuitive understanding of what constitutes a shadow.

> Lara: Well, I don't think it is, because, um, it's like Larry said a shadow's blocked light. He thinks it's blocked light, which is what I think. At night, well at night we're just turned away from the sun, so, I mean, I guess, yes it sort of is that the other part of the earth is blocking the light, but I think that, because we're just turned away from it, I don't really think it is. But if we were facing the sun and the moon or something, like an eclipse, crossed the sun, then it would be a shadow because it's blocking the light.

For Lara, the idea of nighttime as a self-shadow of the earth was not satisfactory. Although she had not fully worked out a definition of shadows that was satisfactory to her, she did not want to relinquish the idea that the term refers to a two-dimensional image thrown onto a surface (as happens during a solar eclipse). The school day ended soon after Lara raised her concerns, and the children went home before they had exhausted their exploration of the meaning of the term *shadow.*

Analysis of "What Is a Shadow?"

This story illustrates the use of background knowledge, as well as the way children can use physical and conceptual objects to reason about the meaning of a term.

The children's ability to draw on their substantial background knowledge of shadows was one feature this exploration had in common with the work of scientists. In addition to their everyday experience with shadows, the class had been observing, measuring, and analyzing shadows for several months.[5] This experience gave some children who rarely participated in science discussions grounds for presenting their own ideas, and arguing with the ideas of others. Despite this experience, however, the group found defining the term, "shadow," surprisingly difficult.

In their discussion of shadows, the children faced two challenges that are important in constructing definitions: developing a satisfactory definition of the term, and clarifying ambiguities about the scope of the term. Both of these issues were brought to the fore by the special case of "nighttime," which served as an "object to think with."

Definitions vary in the degree of precision and formality. When the intended scope of the term has ambiguities or fuzzy boundaries, a philosophically sophisticated person would not expect a compact analytic definition to be available. Recognizing and responding to differences between the extension of a definition (its scope) and the range of phenomena to which the definition might apply is an important dynamic in science and was addressed in the discussion of the definition of syphilis. Over a period of hundreds of years, changes in the understanding of what syphilis is interacted with how it was defined.

For many purposes, it is adequate to use a prototypical or "normal" case as the basis for identifying the scope of a term. For example, a robin might exemplify the term, "bird," because it has the salient characteristics of a bird: it flies, it has feathers, and it lays eggs. Jenna's example of the shadow cast by a pen on the table, due to light coming

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[5]In the following chapter it will be seen that, the children's relative inexperience with the phases of the moon probably made their thinking about them less robust.

through the window, showed the characteristics of the "normal" case for a shadow. Her discussion explicitly identified two features of shadows that had not been noted by other children, the role of the surface and the direction of the light. Although this description corresponded to what most children probably thought of as the "normal case" of a shadow, especially in the context of the shadows curriculum, the children preferred Larry's vivid and succinct description of shadows as "blocked light." Before the question about nighttime was asked, they probably assumed that both definitions had the same extension.

A special case may force one to reevaluate both one's definition and one's understanding of the term. For example, a penguin does not fly and clearly fits neither the definition nor the normal case of a bird. However, considerations of anatomy and evolution gave scientists reasons to expand their understanding of what birds are, and broaden the term to include penguins (Sometimes only one of the two extensions changes. For example, after the discovery of spores resistant to boiling in water, the concept of what it means for something to be sterilized did not change, but the operational definition of sterilization did.) For the children, the special case of "nighttime" raised similar issues about shadows.

Nighttime does not correspond to the normal case of a shadow, in which the blocking object and the surface are assumed to be distinct, as was the case in Jenna's demonstration with the pen and the table.[6] Another difference between nighttime and a "normal" shadow is that it does not darken only the "back" surface of the earth , but also engulfs the three-dimensional objects on it, such as ourselves (a corresponding region exists for the "normal case," but our attention is drawn to the two-dimensional projection on the surface).

By asking the children to apply Larry's definition to the case of nighttime, Dave put it to more formal use than was originally intended. Although the children may have

[6]"Normal," of course, is determined by experience. A skilled painter of still lifes, for example, would readily consider the dark side of a pear to be a shadow.

implicitly assumed that "blocked light" involved a blocking object and a surface that were distinct, their affirmative responses to Dave's question, "Is nighttime blocked light?" shows that they realized this is not explicitly required by the definition. Some children retained the definition and accepted the consequence: nighttime is a shadow, although a counterintuitive one. Others, such as Lara, saw this case as highlighting the inadequacy of the definition. This shows that at times a definition may be changed in order to accommodate a more strongly held belief and that at other times one may change one's belief about which things belong in the scope of the definition. The children who continued to accept the definition of a shadow as "blocked light," accepted the implication that nighttime must be included in its scope.

The children in the class struggled with an aspect of the constructing definitions process that is important and sometimes challenging for scientists — dealing with discrepancies between the scope of one's current definition of a term and one's less formal understanding of what the term's scope should be. Many of them shared the attitude of surprise — and pleasure — expressed by one of the boys after class, that something as "simple" as shadows could be so hard to explain. In contrast with children, scientists are more aware of this kind of discrepancy and have strategies for dealing with it. It is not uncommon, for example, for them to use looser definitions in the initial stages of an investigation and expect to refine the definitions as part of an iterative process.

Operational Definitions and Confounding Factors

In the following two learning stories the children construct operational definitions as a part of designing and conducting experiments.

<u>The Pet Races</u>

As previously discussed, difficulties developing a satisfactory operational definition of sterilization complicated the debate over spontaneous generation. A difficulty that was much simpler to identify arose for two girls who designed the following "pet races" as a comparative measure of sense of smell.

I learned about the pet races during my initial interview with Amy, a girl who rarely became enthusiastically involved in science activities.[7] She told me about an experiment she and a friend had conducted for the previous year's school science fair. The girls had decided to find out whether Amy's pet hamster, or her friend's pet mouse, had a better sense of smell. Their "hypothesis," Amy explained was that the two animals had the same sense of smell. To test this hypothesis, they built a maze and put food in one of four places, assuming that the animal with the better sense of smell would be the first to find the food. Although they did not use the terminology operational definition, the girls had operationalized "better sense of smell" in terms of the time it took an animal to find the concealed food.

Each animal was to be timed for several runs. Soon after the initial trial, however, the girls encountered a thoroughly unexpected confounding factor. The hamster fell asleep! They tried repeating the experiment after preventing the hamster from eating for two hours. Although this seemed to keep him awake, he was still less active than the mouse. The children concluded that the hamster's low activity level made it impossible to evaluate its sense of smell with this experiment. Amy remarked, "We wanted to try and figure out the sense of smell, but in the end we really couldn't tell what it was. We would have had to do a lot more experiments." Although the problem of confounding factors is well known to professional scientists, it was new territory for Amy.

Amy and her friend found that unexpectedly low activity level on the part of the hamster made a race to find food an inadequate measure of smelling ability. However, after their unsuccessful effort to motivate the hamster by withholding food, the girls did not attempt a new operational definition of the animals' ability to smell. In contrast, scientists

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[7]Amy's active involvement in her science project, which she had chosen on the basis of her own interests, was strikingly different from her involvement in most school science. She described both the times her grandfather talked to her about science, and the class sessions about shadows and the phases of the moon, as "boring." In contrast to her subdued presence during classroom science discussions, she described the science fair experiment with energy and enthusiasm. Her experience illustrates with marked clarity the importance of building science education on children's interests.

may spend years trying to construct and validate an operational definition. The case of sterilization and spontaneous generation illustrated how difficult a process this can be.

The Smell Experiments

The Experiments

In the learning story that follows, two girls construct and refine an operational definition for the term "smell." Because they developed their definition in the context of on-going experimentation, their work, unlike Amy's pet races, incorporated the iterative aspect that characterizes much of professional science.

The "smell experiments" were initiated by Emily and Sally after reading an article in *Science World*, their school science magazine, titled "Do Girls Smell Better Than Boys?" The word play in the title, and the theme of gender differences appealed to the girls, both of whom had earlier raised the question "why are girls more mature than boys?" Hoping that this new question would provide an alternative way of showing female superiority, they spent nine forty-five minute sessions designing, implementing and analyzing three experiments that would measure differences in their classmates' sensitivity to smell.

The method described in the magazine involved six successively more dilute solutions. The purpose of the procedure was to find a "threshold smell" for each participant; this would be the lowest of the concentrations they could identify. The implicit operational definition of "better sense of smell," therefore, was the ability to detect a lower concentration of peppermint oil. However, over the course of their experiments the girls made significant modifications both to the design of the experiment, and to the corresponding operational definition of "sense of smell." These modifications were motivated by their respective understandings of "sense of smell," and by their efforts to eliminate confounding factors. They also became increasingly aware of the importance of determining a dilution that would enable them to identify individual differences in people's sense of smell. Because the emphasis in this section is the construction of operational definitions, and handling potentially confounding factors, only enough additional description to clarify the flow of events will be included below.

Some of the first changes they made to the experiment were motivated by their understanding of the human sense of smell, as influenced by information presented in the *Science World* article. The girls responded strongly to different points made by the article; their differing understandings sometimes led them to suggest different operational definitions of sense of smell.

Sally was most impressed by the fact that there are different olfactory neurons for detecting different kinds of smells, such as sweet, sour, etc. This led her to suggest a significant break with the original experiment. Instead of using one smell, which would presumably measure gender differences in only one type of olfactory neuron, she proposed that they use many smells. "Oh," she said, "I would put *different* smells in them ... So I would say, like, you would have to identify the smell." Together, the girls elaborated on this idea, proposing peppermint, cherry, and almond extracts as possible scents.

In contrast to Sally's focus on different types of smell, Emily was more intrigued by the fact that we have about 10,000 olfactory neurons which, she noted, "send messages to your brain in, like, milliseconds." In the course of the experiments, it became clear that Emily believed that having more olfactory neurons, rather than different ones, was equivalent to having a better sense of smell (for example, she later interpreted small average differences between girls' and boys' smell experiment scores as corresponding to small individual differences in the number of olfactory neurons possessed by girls and boys). This led her to make a suggestion that built on Sally's idea of using multiple smells: "Oh I have an idea— we can *combine* them [the ideas] so that you have to say, you have to identify the smell and then identify how much is put in, like a lot, medium, or little. O.K.?"

When Sally agreed to this compromise, the general plan for their experiment was set. The girls' proposed experiment differed from the original experiment in several ways. First, it used a variety of smells, rather than one smell. Second, the intensity of each smell was to be evaluated as "little," "medium," or "big" (although they later eliminated the medium category as ambiguous.) Thus, their operational definition emphasized both an ability to recognize a variety of smells and the intensity with which the smell was perceived.

Now that they had agreed on a general plan, the girls specified the smells and quantities to be used: peppermint extract (medium), vanilla (little), almond extract (big), garlic powder (little), lemon extract (medium), anise (big), and garlic powder (big). As they began implementing their plan, however, they encountered several confounding factors that led them to introduce further changes in their procedure.

For example, on the day of the first experiment, they realized that by looking in the containers, participants could receive additional clues to the identity of the substances. Some liquids had color. Others contained particles of undissolved powders such as pepper. Although the girls thought of blindfolding the participants, they decided that this would be complex and time consuming, in part because the participants would be unable to write down their responses. Furthermore, if answers were given verbally other participants might overhear. Sally suggested the use of food coloring to disguise the liquids, but the coloring was not immediately available. The solution they arrived at, therefore, was to ask participants not to look in the cups.

The girls decided *a priori* on the amounts of the substances to use, but experimented a little before selecting the concentrations. Dan made class time available for them, and offered some useful hints for managing their classmates. Each participant was asked to identify six smells, and whether or not the smell was "little" or "big," and record the result on a special form. With the assistance of her uncle, Emily used a spreadsheet program to compute the average number of items wrong. The result was 2.2 items wrong for the girls and 2.4 for the boys. Her preliminary conclusion was that "girls do in fact have better smell than boys." However, after discussion, she agreed with Sally that any demonstrated margin was slight, and that a more decisive result would be preferable.

In planning the second experiment the girls identified a number of confounding factors from the first smell experiment, and devised strategies for handling them. Emily, for example, argued that they should not use pepper, because, during the experiment, someone "said that the pepper got in their nose and when they went to smell the next one … they still smelled the pepper." This meant that pepper had the confounding effect of making it more difficult to identify subsequent smells.

Another confounding factor was that some participants might be unable to name a smell, even though they were familiar with it. For example, one girl could not name ginger, but recognized that "her mom makes cookies with it." Similarly, Emily noted that "Mia put cream soda for vanilla" which "has a lot of vanilla in it." Therefore, she wondered whether they should count Mia's answer as correct. Sally agreed that "cream soda is basically vanilla," so they added one point to Mia's score. To avoid this confounding factor, they agreed to use familiar smells, although they disagreed as to whether certain specific smells would be well known to all the children.

Emily and Sally also noted that the girls' greater familiarity with the smells used in the experiment was a confounding factor. As Emily stated, the experiment was "fine, but it didn't really, like, prove a point. I mean it kind of said that girls were better than boys, but then again, girls are more familiar with smell than boys are because we do more stuff in the kitchen." In response, they decided to use smells that would be equally familiar to boys and girls.

The girls recognized another problem in addition to these confounding factors: their test was not sensitive enough to detect small differences in smell ability. They concluded that a more challenging test was needed in order to separate the girls from the boys, and went on to debate the best ways to construct this greater challenge. Again their differences of opinion reflected their individual "takes" on smell, and suggested different operational definitions.

Emily argued that they should use a small amount of one of the more challenging smells from the first experiment because that "just gives us a bit more information ... If we just put an itsy, itsy bit ... because you really have to use your sense of smell and if boys don't have as much—" Her comment that "if the boys don't have as much" reflected her belief that having more olfactory neurons corresponds to a better sense of smell. In her view, those with more neurons should be able to detect smaller amounts of the smell.

Sally did not agree that using only one smell would be a better test. In her opinion, it was important that "you have different, you know, those olfactory neurons" because

> If you have ... one sort of smell and your nose is sort of trained to smell that sort of smell like you could have a salty smell, you have a spicy smell, a sweet smell and all those different kinds of smell. A bitter smell and a sneezy smell like pepper.

She drew the conclusion that, "different noses need to have different types of smell" to do their best work. From this perspective, a good strategy would be to find particular smells that girls' noses could detect more readily than boys' noses.

Emily voiced her disagreement with Sally, claiming that "we pretty much all have the same sort of smell." Sally countered that, "if you gave them [the participants] all the smells, then it might give them a chance to shine." This was one of the few times at which the two girls had a disagreement that was strongly rooted in their respective understandings of smell (in contrast to their disagreements over what was socially feasible, or their tendency to find objections to whatever the other was saying).

Initially they compromised by planning to use two well-known smells, apple juice (which they had both chosen) and pineapple juice (which was Sally's choice, because she argued for a variety of smells). However, because Sally forgot the pineapple juice on the day of the second experiment, Emily's "operational definition" was put into action and they used one weak concentration of apple juice. The girls wanted to find a concentration to which girls, but not boys, would be sensitive. "If the boys can't smell it," Emily explained, "then we've proved our point."

With their goal of finding a discriminating concentration in mind, the girls prepared the smells more systematically than they had previously. They put a small amount of apple juice in a cup, and kept adding water until it became almost too dilute to smell. The one unfortunate side effect of this careful and time consuming process was that it limited the amount of recess time available and the number of children tested. The girls thought they did not have enough data to merit analysis, and they decided to try again another day.

For the third experiment Sarah and Emily used a different method for finding a critical dilution of the test smell. They began with one cup of water and used an eye dropper to add .5 ml of apple juice at a time, until *they* could both smell it. They decided that 2 ml of apple juice to one cup of water was a good ratio because neither my assistant nor I (both male) could smell it, but they could. This time each of them recruited and tested participants, and they had an entire recess period available. Their analysis found that 28% of the 18 girls tested could not identify the smell, in contrast to incorrect identifications by 44% of the 16 boys. They were pleased with the results, which they interpreted as confirmation of girl's superior sense of smell.

Analysis of the Smell Experiments

The following section begins with a brief recapitulation of the girls' iterative process of definition and experimentation. The analysis then emphasizes two major themes that were used in the analysis of the history of science episodes: the role played by their experience and beliefs in the cycle of design and interpretation of the experiments, and the progressive development of the girls' conceptualization and operationaliztion of smell.

According to the operational definition implied by the *Science World* experiment, one person had a better sense of smell than another if they were able to identify a weaker concentration of peppermint oil. For their first experiment, the girls developed a variation of this definition, which measured the number of correct identifications of a group of seven smells by name and strength ("little" or "big"). They subsequently dropped the identification by strength, which did not prove to be useful. They further changed the operational definition by requiring any smells they used to be well-known to the children and easily identifiable by name at full strength. This change was motivated by differentiating the following possible results of a smell attempt: failure to detect a smell, unfamiliarity with the smell, inability to recognize a smell, inability to recall the name of a smell, and recognition of a smell that is not known by name. Finally, the girls aimed to make the dilution of the smell a critical one — one that they hoped would be too difficult to identify for many boys, but identifiable for most girls.

The smell experiments conducted by Emily and Sarah provide a good illustration of the iterative nature of the process of definition and experimentation. This process was influenced by the girls' personal experience, as well as by the theoretical ideas and framework they derived from the *Science World* article. Both types of "background knowledge" impacted on the way they conceptualized smell. This conceptualization required eliminating several confounding factors, and resulted in a clearer delimitation of the scope of the term.

The Influence of Experience and Beliefs on the Iterative Process

The experiences and beliefs that shaped the children's original operational definition and the subsequent interpretation of results and redefinition were threefold: their cooking experience, their research paradigm (or experimental framework) and the theoretical framework of olfactory neurons.

Personal Experience

The girls' experience had a clear impact on their choice of smells, and on the way they used these smells. More specifically, their experience with cooking led them to choose the scents that were available in their kitchens at home. Sally was the more experienced cook, and displayed the most confidence in suggesting how much of each substance to use. However, the girls' cooking experience may also have been misleading at times. Perhaps because they did not realize that smell is more sensitive than taste, they tended to make their solutions too strong, and possibly recognizable even to poor smellers.

Experience with cooking also helped the girls understand and evaluate some of their classmates' responses. For example, because they knew that the girls in their class probably had more experience cooking than the boys did, they were able to eliminate this potential confound from the second and third experiments. Their familiarity with cooking ingredients also enabled them to interpret and evaluate inexact responses. For example, when one of the girls said that ginger was something her mother put in cookies, they charitably interpreted her observation as a reference to gingersnap cookies. Similarly, because they knew that vanilla is a key ingredient in cream soda, they were able to decide whether or not to give Mia credit when she labeled the vanilla, "cream soda."

The *Science World* article provided the foundation for the experimental design used by the girls. It was also the source of important theoretical ideas about smell — particularly those that involved "olfactory neurons" — and influenced the way in which the girls developed operational definitions.

Experimental Paradigm

Although the girls changed the original experiment substantially, they used it as a foundation for their work. For example, the instructions for the original experiment included administering a test and using a diluted smell. Emily and Sally ultimately built both of these features into their own experiments. Consistent with the magazine instructions, the girls also required their participants to identify the smell by name; this is a clearer measure of recognition than simply requiring the participants to detect the presence of an unnamed odor. Finally, the original experiment operationalized the criterion for smell as the ability to detect weaker concentrations of the peppermint oil (alternative operational definitions might have stressed the ability to recognize a wide variety of smells, the ability to distinguish similar smells, or the ability to remember smells). The girls also used the criterion of identifying a dilute scent in their second and third experiments.

Building on this basic framework enabled the girls to engage in a successful iterative process of experiment, implied operational definition, and revision. In this respect, the girls' process was similar to that of the 'spontaneous generation' experiments. Those experiments also shared a common design, which involved sterilizing a growth medium, allowing time for life to develop, and testing for signs of life while avoiding errors due to contamination. This allowed researchers to focus on the key aspect of sterilization. It also gave them a common framework for discussion and interpretation of the results. For Emily and Sally, the experiment in the *Science World* magazine served as the equivalent of a research paradigm such as the one shared by the French experimenters. Because they worked within the framework provided by the magazine, they were able to focus on which smells to use and at which concentration.

The Role of the Girls' Theoretical Framework

The article also provided the girls with a theoretical framework for thinking about smell. Both of the girls used the concept of "olfactory neurons" in analyzing their results and proposing directions for experimentation. As was noted in the narrative, Sally emphasized the role of the different kinds of olfactory neurons while Emily was more interested in the number of neurons.

The girls' beliefs about olfactory neurons played a role in their initial design. Each girl used her understanding to introduce a new element to the first smell experiment. Sally's argument for the importance of different types of neurons led the girls to use a variety of smells. Similarly, Emily's understanding of the correspondence between smelling ability and number of olfactory neurons led them to require participants to identify the strength of each smell as little, medium, or big. The resulting research design, therefore, reflected the views of both girls.

The next step in the iterative process involved interpreting the results of the first experiment, and improving the design. Again, the girls' different emphases guided their respective responses. Emily interpreted the lack of decisive results showing female olfactory superiority as due to the insufficiently challenging dilutions. Sally, in contrast, suggested that the key lay in finding a smell that would allow girls' noses "to shine." In response to Emily's concern, the solution used in the second and third experiments was highly dilute and required greater smell sensitivity for success. Taking Sally's concern into consideration, the girls decided to use two smells, rather than follow Emily's preference for using just one smell.

In summary, the girls drew on a variety of background experiences and beliefs in intuitively constructing their operational definitions of "better sense of smell." Among the most prominent influences were: cooking and other personal experiences, elements taken from the design of the smell experiments in the magazine, and ideas about olfactory neurons

Delimiting the Scope of Terms and the Iterative Process

As was first addressed in the discussion of defining syphilis, delimiting the scope is a crucial part of constructing definitions. This is frequently an iterative process because the initial understanding of the relevant phenomena is not adequate to conceptualize what should be in the scope of the term and what should not. The syphilis story showed that it may be necessary to narrow the scope of a term, for example differentiating things which have been conflated, such as the venereal diseases syphilis and gonorrhea. Broadening a term's scope, as was done to include the advanced stages of syphilis may also be required. Delimiting the scope of the term "sense of smell" was an important part of the conceptual work done by the girls in creating their operational definition, which will be now be analyzed.

The key measure of smell used by the girls was the participants' ability to correctly identify a smell or set of smells by name. Each girl had an implicit, possibly developing, understanding of what the term sense of smell means. As they prepared and analyzed the experiments, they identified a number of factors as being extra-olfactory — that is not to be considered essentially smell related for the purpose of their experiment. The color or appearance of the smell solutions was a factor they decided to eliminate while designing the first smell experiment. For them, if a judgment could be based on, or enhanced by, visual appearance, it would not be a purely smell-based discrimination. The girls also tried to eliminate other cues, such as overhearing the responses of other participants, which might result in "cheating" or might enhance a person's ability to identify a smell. At times, however, the girls violated their own standards by giving hints, such as the hint they gave to the girl who associated ginger with her mother's cookies.

Most of the other factors of interest concerned the connection between naming and smell. The girls accepted from the *Science World* experiment that it was not sufficient to simply detect the presence of a smell, but that identification of a smell by name was also important. However, they identified after the experiment several reasons why the test might not be a pure measure of smell. Participants might fail to name the smell because they were unfamiliar with it; because they knew they had smelled it before but could not remember the context; or because they had clear recognition of it but did not know the name. The girls addressed these possibilities in discussing special cases involving ginger and vanilla, as well as the presumed greater familiarity of their female classmates with spices used in cooking. Their resolution to this problem was the selection of a smell with which they were convinced the children would be familiar, so familiar that they would have no trouble naming it once detected.

Smell Conclusion

The smell experiments, which the girls developed completely at their own initiative, were the most extensive investigation undertaken by the children with whom I worked. It is not surprising, therefore, that their process exhibited more features of mature science practice than the other investigations. For example, they employed an iterative cycle of designing, performing and analyzing experiments, in order to demonstrate to their own satisfaction that "girls smell better than boys." Furthermore, they were guided in this process by the theoretical framework of olfactory neurons.

However, one can see there was room for their seeds of the practice of constructing definitions to grow, since the girls missed opportunities to apply these ideas more comprehensively and thoroughly. For example, although Sally referred several times to the existence of special olfactory neurons for detecting smell categories such as sweet, bitter and sour, the girls did not use these categories to help guide their selection of smells.

Another example, concerning their analysis of the final smell experiment is that neither of the girls noticed that most of the incorrect responses identified the diluted apple juice as watermelon, grape juice or another sweet smell. This result could have been interpreted as evidence that sweetness is a significant characteristic of certain smells, consistent with the idea that there exist olfactory neurons are specialized to detect sweet smells.[8] These examples indicate ways in which a seed of science practice may differ from a more developed form.

Conclusion

The process of constructing definitions plays an integral role in the practice of science. Furthermore, as the learning stories show, rich opportunities for constructing definitions can arise naturally in the course of children's science inquiry, and many children find the process very engaging. The construction of definitions therefore deserves greater attention from science educators.

Like the scientists discussed in the historical episodes, they worked to establish the scope of terms, create operational definitions, and identify confounding factors. They stimulated one another's thinking through argument and counterargument, and the use of special cases as objects to think with. As in the previous chapter, the children's thinking and activities were analyzed with attention to the influence of background experiences and beliefs. An important characteristic of many processes in science highlighted in the stories is that the construction of definitions is frequently not a one pass process, but rather an iterative one.

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[8]To test this further one could explore whether people make similar misidentifications if they are given weak concentrations of substances which smell bitter, salty or sour. However, in analyzing what the girls did and did not do, it should be kept in mind that the girls were mainly motivated to show gender superiority, not to explore or validate ideas about the sense of smell.

Chapter 6: Models

Introduction

Unlike questions, contradictions, and constructing definitions, the role of models in science learning has been a topic of extensive study by science educators (Brown, 1990; Chi, 1992; Clement, 1983; Dyche et al., 1993; Gentner & Stevens, 1983; Gilbert, 1991; Grosslight, Unger, & Jay, 1991; Linn & Songer, 1991; McCloskey, 1983; McCloskey & Kargon, 1988; Raghavan & Glaser, 1995; Schaubel, Glaser, Raghavan, & Reiner, 1991; Sherin, diSessa, & Hammer, 1993; Stewart, Hafner, Johnson, & Finkel, 1992; Webb, 1993; White, 1993; Wiser, Grosslight, & Unger, 1989; Wiser, Kipman, & Halkiadakis, 1988). Nevertheless, as the following story will illustrate, we may be surprised by the interpretations children give to their experiences with models.

Story: "Can you tell me *why* the moon has phases?"

To foster the children's exploration of the moon and its phases, Dave introduced "moon-pops" – tennis balls impaled on sticks, which they held at arm's length and moved in circular orbits by slowly turning their bodies around. The intense light of a projector shining on the moon-pop illuminated a portion of the tennis ball. This gave the children the opportunity to observe the phases of the moon. After several opportunities to explore with the moon-pops, draw pictures of the phases, and discuss their findings, most of the children appeared to understand the connection between the moon-pop's position and the corresponding phase of the moon.

During an end of the year interview, Mara's explanation was particularly clear. Her drawing, for example, was similar to one often found in textbooks, with the moon shown in several positions around the earth and the halves of the moon facing away from the sun shaded in. Using the drawing as a reference, she correctly explained how the moon looked from earth for each position.

We went on to discuss other topics, and as our interview came to a close I asked her if she had any questions for me. "So," she responded, "could you tell me *why* the moon has phases?" After recovering from my initial surprise, I asked her questions so I could better understand her thinking. I discovered that Mara saw the moon-pop model as a way of producing the *appearance* of the moon phases. She believed it was a clever trick, which, for her, did not explain why the moon undergoes its monthly changes. In subsequent interviews, I found that several other children shared this view, which despite its important consequences for science learning, could easily have gone undetected.

In the body of the chapter it will be argued that Mara thought of the moon-pop model as a *surface model*, a model that captures the appearance of something without explaining it or revealing the mechanism behind it. Dolls and model airplanes are examples of surface models that are familiar to children. In contrast, Dave and I assumed that the model would be interpreted as an *explanatory model* — one that shows how changes in relative positions of the earth, sun and moon cause the phases of the moon.

An examination of children's interpretations of models as surface or exploratory is an example of the way this chapter uses children's attempts to understand the phases of the moon to analyze several aspects of their understanding and use of models. The data will also be organized and analyzed using the frameworks of *constructionism* and *connectedness*, and the concepts of *ready-made models* and *models in the making*. My observations and analysis will be used to bring out weaknesses in some of the ways that science educators have classified and made use of models. At the least, they will show that science educators would do well to look more closely at how children actually use and construct models — and especially at the meanings they derive from their explorations.

Relevant Literature on Children's Understanding and Use of Models

The use of models has received a great deal of attention from science education researchers and curriculum reformers (e.g., AAAS, 1990). Some have even gone so far as to place models at the center of science, characterizing science as essentially "a model making activity" and arguing that science education should be structured with this in mind (Gilbert, 1991).

Many educational researchers would agree that a model can be approximately defined as "a simplified imitation of [something] that we hope can help us understand it better" (AAAS, 1993, p. 168). They would probably also agree that important uses of models by professional scientists include: helping concretize concepts, clarifying complex phenomena, predicting trends, and explaining mechanisms and processes (Raghavan & Glaser, 1995). However, they disagree as to which concepts for analyzing models and which objectives for children's use of models are most important.

Goals of Research into the Use of Models

The goals of research on models include: understanding children's understanding of models (Grosslight, et al., 1991); identifying differences between the mental models used by novices and experts (Chi, Feltovich, & Glaser, 1980; Gentner & Stevens, 1983; Larkin, 1983); and teaching model-based reasoning skills (Raghavan & Glaser, 1995). Two contrasting approaches are those of researchers who design computer models and environments to foster understanding of specific content areas such as Newtonian dynamics (diSessa, 1982; Sherin, diSessa, & Hammer, 1993; White, 1993) and thermal phenomena (Linn & Songer, 1991; Smith, Carey, & Wiser, 1985; Wiser, et al., 1989) and those who create tools such as programming environments with which children can build their own models and simulations of phenomena that interest them (diSessa & Abelson, 1986; Papert, 1980; Resnick, 1994; Wilensky, 1993).

The analysis in this chapter has goals in common with several of the research approaches mentioned above, as well as substantial differences in goals, philosophy and methodology. For example, it shares with Grosslight et al. an interest in children's understanding of models, but differs in its fundamental emphasis on using concrete examples from the children's explorations to understand aspects of their thinking that might be overlooked by researchers using a broader level of epistemological analysis.

Like some of the studies mentioned above, this chapter focuses on children's exploration of a specific domain — in this case the phases of the moon — and makes use of an understanding and analysis of both the subject domain and the difficulties frequently encountered by learners engaged in its study. Furthermore, it shares with some of these studies an interest in the iterative process of model design and revision. The purpose of the curricula involved, however, is different. Other studies focus on applying the researchers' theoretical beliefs through the creation of an effective environment or curriculum for learning about the domain in question. In this study, the curriculum was developed by the teacher, not an outside researcher. In addition, the primary goal of his curriculum was not to teach the children about the phases of the moon, but to provide a venue for the children's sense-making activity. Finally, the data was analyzed with an eye to discovering the seeds of mature science practice in the children's activities and thinking, rather than emphasizing their subject matter performance.

Epistemological Issues Concerning Children's Understanding of Models

In the following sections I address and critique two distinctions found in the literature on models and science learning: the distinction between physical and abstract models, and a classification that evaluates the sophistication of children's epistemological understanding of models. I then introduce two alternative distinctions I found useful for analyzing the children's creation and interpretation of models: one between models in the making and ready-made models, and one between surface and explanatory models.

"Physical Models" Versus "Abstract Models"

One way in which models have been categorized is by differentiating between "physical models" and those that are classified as either "abstract models" (Grosslight, et al., 1991) or conceptual and mathematical models, which include computer simulations (AAAS, 1993). Some researchers see this as an important distinction, and suggest that it is desirable for children to quickly move beyond physical models (Raghavan & Glaser, 1995). However, the analysis in this chapter of children's use of models that were primarily physical shows that a division between physical and abstract models is not a particularly useful one. Rather, the children's explorations show that physical models can raise many of the most important epistemological issues associated with more "abstract" models. I will also argue that it is the palpability of some non-physical models (such as one boy's mosquito-bat model of lunar eclipses) that support the connectedness that makes them effective. Finally, I will argue that whether or not the model is physical does not determine issues important for thinking about models: children's interpretation of models, and whether children are creators or consumers of the models they use.

The Epistemological Levels of Grosslight, Unger, and Jay (1991)

Researchers employing distinctions such as physical versus abstract models may also devise criteria for classifying models along epistemological lines. Unlike the physical versus abstract distinction, which concerns only attributes of the model, epistemological distinctions include the model user or model maker. At times, however, these may be epistemological issues that are important to the theorists, but not to the children themselves. Grosslight et al. (1991), for example, developed a framework that involves three epistemological levels of understanding models. The first level views models as "simple copies of reality" (p. 817), which can differ in size from the original. Thinkers at this level are unaware of the many choices required in building a model. In contrast, a second-level thinker realizes that model builders make specific choices that are driven by the purpose of their models. However, they do not think of models in terms of underlying ideas. A level three thinker understands that models can be used to develop predictions based on underlying ideas. These predictions can be tested by comparing them with empirical data, and the model can then be refined.

The categorization scheme of Grosslight et al. is hierarchical. A potential problem with such classifications is that they assume a normative view of the nature of science and models. The epistemological levels of Grosslight et al. reflect an idealized view of science that is shaped more by philosophers of science than the actual practice of science. In contrast, Turkle and Papert (1991) make a strong case for epistemological pluralism — the value and legitimacy of multiple approaches to problem solving and creating artifacts. These issues have been pursued by feminist analyses of science, such as those of Harding (1991) and Keller (1985).

A pitfall of hierarchical schemes of categorization, which is, in part, a consequence of their normative status, is that they can lead to curricular approaches that take as a goal moving children up the hierarchy. An important argument of this chapter is that such approaches fail to recognize much of the richness of physical and other "lower ranking" categories of models. For example, a pilot study by Raghavan and Glaser (1995) included an attempt to accelerate children's progress through these epistemological levels.[1] They implemented and assessed a curriculum they call Model-Based Analysis and Reasoning in Science (MARS), which is designed to teach middle-school children about models and model-based reasoning. They report that most students began at Grosslight et al.'s Level 1. After completing the project, however, most had attained Level 2, and many of the students "displayed an understanding consistent with Level 3" (p. 57).

In contrast to the hierarchical classification schemes critiqued above, the categories of models discussed in this chapter are complementary. The first category is *ready-made models* and *models in the making*, and the second is *surface* and *explanatory models*. The relationship between the members of each pair is similar to that between ready-made science and science in the making in two ways. First, both members of each pair are important for the practice of science. Second, progress in science often involves an iterative process of investigation in which the emphasis may shift back and forth between the two types of models.

One difference between the research approach of Grosslight et al. and the approach taken in this chapter is that their approach is driven by a top-down agenda of what they

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[1]One of the first responses of American educators who met with Piaget at Woods Hole in 1959 was to inquire how progress from concrete to formal operations could be accelerated. Piaget referred to this as the "American problem" (Bruner, 1960).

think children should know about the nature of models rather than a more bottom-up approach built on observations of the thinking and activity of a particular group of children. As a result, they tend to focus more on the deficits of the children, measured in comparison to experimental scientists. In contrast, I attempt to identify the positive elements of their thinking and practice, as well as ways their learning environments may encourage incorrect conclusions or fail to support the growth of their understanding of models.

Approach to Models Taken in this Chapter

My primary emphasis is on understanding children's thinking, not on changing it. In particular, I am interested in identifying elements of the children's science practice which, examined in light of their background experiences, can be viewed as seeds of mature science practice. This approach, combined with a finer grain of analysis, shows that the children are grappling (although not necessarily consciously) with important epistemological issues, as was the case with the children's attempting to delimit the scope of the term, "intelligence."

To carry out this analysis I develop two distinctions that involve the relationship between the model and the model user. One distinction, that between "ready-made models" and "models in the making" depends on the context of the model's use and creation. The other distinction, that between surface and explanatory models, addresses the model's function either as intended by its construction, or as interpreted by a user. Surface models illustrate the appearance of a phenomenon while explanatory models clarify why it happens, as was introduced with the story of Mara and the phases of the moon.

"Ready-Made Models" and "Models in the Making"

The distinction between "ready-made models" and "models in the making" is analogous to that between "ready-made science" and "science in the making." Like ready-made science, ready-made models embody well established ideas and theories. As such, they are valuable tools for carrying out routine calculations and predictions (e.g., models that determine the aerodynamic lift produced by a particular wing design, or the occurrence of lunar eclipses). Most models used in classrooms are ready-made models. For example, one can purchase models designed to demonstrate the phases of the moon.

In contrast to ready-made models, "models in the making" are being developed and tested as part of science in the making. For example, several competing models have been developed to analyze the risk of global warming due to industrial pollution and other factors. Rather than reflecting well established and non-problematic theories, the ideas and implications of these models are still being explored and worked out.

Surface and Explanatory Models

The moon-pop story, "why are there phases?" illustrates another distinction between two types of models: those that capture the appearance of a phenomenon — surface models, and those that include the "mechanism" that makes the phenomenon occur — explanatory models. Thus, the word explanatory is used in the sense of "causal explanation." This does not imply that surface models have no explanatory value. In fact, the distinction between surface and explanatory models is not an absolute one. A model may be surface for some people or purposes, and explanatory for others. For example, Dave designed the moon-pops as an explanatory model to help the children construct a causal understanding of the moon's phases. Mara was able to use the moon-pops to visually recapitulate the phases of the moon, but recognized that this did not satisfy her desire to understand the *cause* of the phases. For Mara, therefore, the moon-pops served as a surface model, but not an explanatory model.

The following examples from the history of science will be used help clarify the differences between surface and explanatory models. Since in some cases explanatory models have clear advantages over surface models, examples which show why surface models are important for the practice of science are included.[2]

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[2]The word "surface" may have connotations of shallowness for some. However, it is more compact than alternatives such as "appearance providing" models.

Eudoxos of Knidos developed a celestial model that was satisfactory for some people, but not others. The key achievement of the model was that it expressed the erratic retrograde motion of the planets as a composition of the highly regular motion of spheres. It was a surface model that revealed the hidden geometric beauty and regularity behind the apparent disorderly motion of the planets.[3] Therefore it was satisfactory for Plato and many of his followers, who were more concerned with finding geometric order than causal or mechanistic explanations. However, the lack of mechanical connection between the spheres made the model inadequate for Eudoxos himself, who was at heart more a physicist than a mathematician. This view was shared by Aristotle who required a model that incorporated a physical causal mechanism. He was able to enhance Eudoxos' model by adding gears that transmitted the motion from sphere to sphere, thus transforming it into an explanatory model.

One function surface models serve is to inspire new ideas, or give them initial plausibility. In 18th century France, mechanical automata in the form of animals were popular with the wealthy, and reached a high level of craftsmanship. (This was noted in a footnote to the analysis of the children's discussion about computers and intelligence.) These automata were seen as surface models, since no one believed that the movement of live animals actually relied on gears and springs. However, the increasing sophistication of these models led Julien de la Mettrie and other thinkers to argue that in principle all human actions, even thinking, could eventually be understood in mechanical terms. Hence, although the primary function of these models was entertainment, they also served to support the plausibility of what was then a radical way of thinking about life.

It should also be noted that although some explanatory models also capture the appearance of the phenomenon modeled, not all of them do. Hence a satisfactory explanatory model is not necessarily a satisfactory surface model. This point is illustrated

[3]This irregularity, in contrast to the regularity of the "fixed stars" was the distinguishing feature of the planets. The word *planet* comes from the Greek word for "wanderer."

by the following example. Researchers seeking to answer the question "What stimuli account for the level of aggressive behavior between two male turkeys?" tested their hypotheses by confronting live male turkeys with assorted turkey models (Science, 1996). They used models that were more schematic than realistic. From the human perspective, they were definitely not adequate surface models. The researchers found that the key element to which the turkeys responded was the length of the model's snood (in turkeys this is a fleshy appendage hanging below the animal's beak). Turkeys were aggressive towards models with snoods shorter than their own, but deferential to models with longer snoods. This behavior pattern was replicated for interactions between live turkeys, so the models sufficed to explain the turkey behavior.

The previous examples indicate that surface and explanatory models may serve different purposes. Surface models may solve practical problems, reveal the simplicity or regularity behind a complex or apparently erratic behavior, or be the first step in a new direction, supporting the plausibility of a more ambitious agenda. On the other hand, the purpose of explanatory models is to promote understanding of how or why something happens. This may be accomplished by highlighting the principle or mechanism that underlies the phenomenon modeled. Such models may be refinements of surface models, or may not even bear a close resemblance to the thing modeled.

The Children's Explorations with Models

This section explores the general ideas about models introduced above in the context of a curriculum Dave developed for exploring the phases of the moon. For example, Dave's curriculum contained elements of both ready-made models and models in the making. On the one hand, he provided the children with materials that invited particular kinds of exploration. This constrained the children's activity and created an experience that, in some ways, resembled the use of ready-made models. On the other hand, the actual responsibility for constructing and interpreting the models, and using them to explain phenomena, rested with the children. To varying degrees therefore, the children were engaged in the use of models in the making. The concept of ready-made models and models in the making will be used to organize part of the detailed description of the children's thinking and activities. A brief introduction to the moon curriculum, including a chronological ordering of the activities, will situate the individual activities with respect to the overall investigation. Again, my understanding of the children's thinking about the phases of the moon and the models was based on year-end interviews with the children, as well as observing and participating in the children's model-based explorations.

The Phases of the Moon Curriculum

Dave initiated the moon curriculum in response to the children's interest in an annular solar eclipse the class observed that May. The development of the curriculum was an ongoing process. Dave used each activity to assess the children's understanding and to set goals for the activities that followed. The project continued until the school year ended in late June.

The first two class sessions elicited the children's thinking about the moon. In the first session, the children used dramatization to model their understanding of the yearly movement of the earth, moon, and sun. The following session was a brainstorm in which the children shared their knowledge about the moon. Most subsequent activities used models to foster an understanding of the phases of the moon. Dave introduced a model that represented the earth with an inflatable globe, and will be referred to as the "earth-ball" model. Largely because of problems involving its scale, the earth-ball model led some children to a scientifically incorrect theory. Therefore, Dave supplanted it with an improved model that used tennis balls on sticks to represent the moon. This will be referred to as the "moon-pop" model. Both the earth-ball and the moon-pop models were used by the children individually and in small groups.

After discussing some issues related to scale with Dave, I constructed an accurately scaled model of the earth, moon, the distance between them, and the relative tilt of their orbits. At Dave's suggestion, I then led a whole class discussion to explore why eclipses do not occur each month. The children had difficulty explaining their ideas with diagrams, but one boy invented a novel model — the "mosquito-bat" model — which, for reasons that will be analyzed later, his classmates found helpful and appealing. Finally, as a year-end project, the children expressed some of what they had learned during their investigations of lunar and shadow phenomena by constructing animations using a special piece of equipment, a proximascope.

The Children's Use of Models

Models in the Making

This section describes two classroom episodes in which the children created their own models. These were the models whose use was most in the spirit of models in the making. In the first story a small group of children construct a collective model. This required them to clarify and compare their ideas. In the second story one of the boys expresses his understanding of partial eclipses through a conceptual or mental model. The other children reasoned with this model to answer related questions. Such activities are akin to "science in the making." Rather than use a model that had been built and tested by others, the children created models that reflected their on-going effort to understand the phenomena they explored. The first of these two models was a surface model, and the second was an explanatory model. This will facilitate a comparison of some features of surface and explanatory models.

Acting Out the Movement of the Earth, Moon, and Sun

In the first moon session, Dave divided the class into small groups to model the yearly cycle of the earth, sun and moon. Their task was to dramatize this movement by carrying balls representing each of the three bodies and acting out the roles. As illustrated by the following excerpts from Dave's comments, he emphasized the children's role as model-builders and the importance of pooling their collective knowledge.

> Dave: Your task is to, in your group, do a three-dimensional model ... Decide on and present to each other ... a one-year model of the earth, sun and moon, as best as possible from what you know. It may not be 100% accurate. ... Some people may know a lot, some a little. My

> guess is everyone knows some different pieces, so even those that are absolute experts, listen to others … to hear what other people have to say, because you might be surprised by what another person knows, or questions that they have. So you can explain to them what you understand about it, and then they can maybe bring something else to the conversation.

Two valuable aspects of this model were that it required the children to make their ideas explicit and that it also gave them an opportunity to discuss and potentially reconcile them.

I worked primarily with one group — Mariem, Mary, Lara, Sally, and Marty. I was initially an observer, but later took on a facilitating role to help the children express their ideas, and be listened to by their classmates. The activity began when Mariem, a self-appointed sun, began turning in circles and moving from place to place. Her apparent belief in a spinning and moving sun, however, was opposed by Lara, who insisted that the sun stays in one place and does not turn around. After Sally voiced agreement with Lara, Mariem abandoned her initial idea, and became stationary. Later in the process, Mary re-introduced the idea that the sun spins. Again, however, this view did not receive general support in the group.

The children's ideas about the movement of the earth and the moon also had to be resolved as they constructed their model. Marty — the earth — began walking in slow circles around the sun, carrying a ball to represent the earth. Mary noted that the earth is tilted, and Sally added that it should move a bit faster. Obediently, Marty spun the ball on two index fingers to show the tilt and began walking more quickly. I asked the others whether this circular movement of the earth made sense to them.

> Lara: Right and at the same time that the earth is spinning, the moon is doing the same thing with respect to the earth, so the moon is to the earth as the earth is to the sun.
> Aaron: So why don't we … try having Mary do what the moon does.
> Mary: I don't think the moon moves.
> Aaron: O.K., so what's your idea?
> Mary: I don't think it moves, I think the earth just like moves around the sun.
> Aaron: So where is the moon going to be?
> Mary: The moon is right there, while the earth goes moving around.
> Aaron: Let Mary show what the moon is doing. [Mary stands in one place, and Marty walks around her in circle]. Wait — is he going around the way that you think or how is he supposed to be going Mary?
> Mary: Yeah and the moon stays where it is.
> Aaron: And the sun also?
> Mary: Yeah.

Lara believed that the moon revolves around the earth while Mary claimed that it did not move. With Mary acting the role, the moon was stationary.

Although Mary's initial "stage directions" indicated that the earth should be moving around the sun (as it had been), Marty (the earth) — perhaps hearing only her second, more ambiguous, statement — started circling around her. This model, with the earth revolving around the moon, was not what Mary intended. She then worked to fix the model, and later in the process decided that the moon is not stationary, but rather that it revolves around the earth.

Some groups shared many initial understandings and addressed greater levels of detail in their models. Whereas this group grappled with such basic issues as whether or not the moon moves, other groups quickly agreed that the moon circles the earth as the earth circles the sun. Their disagreements centered on issues such as the period of the moon's orbit. During the class presentation, for example, one group representative said that "the moon goes around the earth 365 times because there are 365 days in the year." A member of another group disagreed, explaining that 365 times is how often the earth rotates in a year. One child added the clarification that the moon revolves around the earth about once every month.

Working on the models, therefore, forced the children to make their ideas more precise and uncovered differences in the children's understanding of the yearly cycle of the sun, moon, and earth. Like the process of constructing definitions, which was frequently driven by argument and counter-argument, differences of opinion frequently shaped the children's model-building. Although some disagreements were discussed, others were resolved by force of opinion.

The Mosquito-Bat Model

The following discussion took place after the children's first model-based exploration of the moon's phases. Since some children concluded that the phases were caused by the earth's shadow, I asked them what we would see when the moon is on the opposite side of the earth from the sun. The discussion that ensued presents a contrast between the effectiveness of a set of models (diagrams) similar to those found in textbooks and a metaphorical model spontaneously created by one of the children.

> Aaron: Say the sun is coming from the direction of the window, and the moon is around here [uses a gesture to show that the moon is on opposite side of earth from sun], then what would we see in terms of the moon?
>
> Brad: An eclipse.
>
> Aaron: O.K. so this would look like an eclipse. But why is it that we don't see an eclipse very often when the moon is going around?
>
> Kevin: Because sometimes the moon goes over, or under, instead of just across.
>
> Aaron: O.K., it goes over or above. Yeah, Peter.
>
> Peter: It doesn't usually line up with the earth and the sun.

These children are correct in their belief that the moon does not line up with the earth's shadow every month. To gain a clearer view of their understanding of the moon's orbit, I asked some of the children to draw pictures on the board. Several of the children's drawings contained elements that made it seem that their understanding was not as clear as their comments suggested. This may have been the influence of pictures they had seen elsewhere. For example, the first child to come to the board drew a solar, and not a lunar, eclipse. Consequently, it is not surprising that many of the children found the drawings confusing.

Looking at the diagrams prompted one of the boys to ask, "How could there be a partial eclipse of the moon?" In response to his question, children made several suggestions: the moon should be smaller, the earth should be further from the sun, the moon should be closer to the earth. They also drew other diagrams, which did not clarify the issue. Brad, for example, drew a complex diagram intended to show that because the sun is so large, its rays are not all parallel. Although this explains how the shadow of the earth is divided into a penumbra, and a darker umbra, Brad's account was too distant from the children's current understanding and thinking for it to make sense to them.

In contrast to Brad's textbook-like explanation of the earth's shadow, his classmate, Jerry, spontaneously created a conceptual model that quickly captured the children's attention and generated a lively discussion.

Jerry imagined that the earth was like a baseball bat, and the light from the sun was like a water balloon, breaking against the bat. The moon was imagined as a mosquito on the other side of the bat. As the balloon broke and the water continued on, the mosquito would stay dry if it was in the eclipse zone (directly behind the bat) and would get wet if it was above or below the bat.

The first child to appreciate the model was Larry, who had introduced the idea that a shadow is "blocked light" but was usually quiet during science discussions. "Oh I get it. Nice choice Jerry. Yes I get it now. The mosquito's the moon, the bat is the earth and the balloon is the sun." The children now began to raise and answer some questions of their own. Emily wondered, "Do other planets and their moons, can they have eclipses too?" This led to speculations about how the frequency of eclipses depended on the size and position of the planet and moon. The children quickly integrated the mosquito-bat model into their explanations.

> S: It [an eclipse] would happen very often because they'd be lined up, but because there's a slant, it's a little more over there.
> B: It splashes over and hits it. [Using the mosquito-bat model]
> S: Yeah if this is the baseball bat, the water splashes over and hits it, but if it's right here [moon lower, and more in line with earth], the water splashes over and misses it.
> [Class claps.]

The chapter discussion will address reasons why this model was effective for the children.

Exploring the Phases of the Moon

The "Earth-Ball Model"

For the next session in which children constructed models, Dave asked them to explore the phases of the moon. "You're trying to build a model that explains why ... we have phases of the moon. Is there a model that can explain it? If a three-dimensional model's too difficult a way to explain it, then use drawings."[4] Although the children had

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[4]Interestingly, Dave's comment indicates that he thought, at least in this case, that a two-dimensional drawing might be easier for some of the children than a three-dimensional model. In mathematics and physics, it may often be easier to express and solve a two-dimensional problem than a three-dimensional one. However, the children had more experience navigating in the three-dimensional universe, and this, as will be illustrated in the discussion of connectedness, may have contributed to their greater facility with three-dimensional models.

the option of drawing the phases, they all preferred to use inflatable globes (which I will refer to as "earth-balls"), about a foot in diameter, to represent the earth, and tennis balls to represent the moon; the light coming in the window provided the sunlight. Most children worked in groups. As illustrated by the following story, however, these materials inadvertently supported a scientifically incorrect explanation of the moon's phases.

As I worked with Larry, he held his tennis ball (the moon) in one hand and slowly moved it around the earth-ball. As the smaller ball moved progressively further into the shadow of the larger ball, I saw the moment of discovery. Based on the changing relationship between light and shadow on the surface of the tennis ball, Larry concluded that he had observed the phases of the moon. They were caused by the passage of the moon through the earth's shadow. "It's because the earth is blocking some of the sun." This "earth's shadow theory" (EST) was discovered by other children as well.

Larry's observation was due to limitations of the earth-ball model. First, the model was not to scale. Given the size of the earth-ball, the to-scale distance of the moon would have been 30 feet. Because of the close proximity of the earth-ball earth and the tennis-ball moon, the most easily generated moon orbits passed through the earth's shadow. Even with a to-scale model, one would need to account for the five-degree tilt of the moon's orbit with respect to the earth's solar orbit to demonstrate why the moon does not pass through the earth's shadow every time it is full.

In addition to his own observations, Larry had another a good reason for misconstruing the earth-ball model. His teacher had given him the materials for the model with the express purpose of discovering what causes the phases of the moon, saying "You're trying to build a model that explains why do we have phases of the moon." Given his teacher's agenda, it was reasonable for Larry to expect the model to produce the desired result.

A Scale Model

After I discussed my observations with Dave, he asked me to lead a class discussion using a more accurate model. I built a scale model of the moon-earth system in which the diameter of the earth was one inch, the diameter of the moon was a quarter of an inch, and the two were 30 inches apart. Building the model was a learning experience for me because although I knew the relevant numbers, I was surprised, as were many of the adults I spoke with, how far apart the model moon and the earth were (they were about 10 times as far apart as they are frequently pictured in books). I also made a separate model that incorporated the five degree tilt of the moon's orbit, illustrating how, during most months, the moon does not pass through the earth's shadow.

The Moon-Pop Model

After taking these points into consideration, Dave introduced a new model — "moon-pops," which were tennis balls on sticks. Using a projector as a light source, the children held the moon-pops at arm's length and turned slowly in place, sweeping the moon-pops in a circle around themselves, and stopping at every eighth of a turn to draw the illuminated part of the tennis ball. Because the children held the moon-pops at arm's length, this model created a greater distance between the earth and the moon, and was therefore somewhat more accurate than the earth-ball models. Using the projector in the darkened room provided an additional improvement because the children were more easily able to distinguish the shadowed portion of the tennis ball from the lighted portion. Dave asked the children to "pay attention to what happens with the lighting on the ball, see if the light changes and to see, if you can replicate, with the movement of the moon around you, all the phases of the moon." He also suggested they pay attention to the relative position of the earth and the sun. In addition, Dave warned the children to avoid the eclipse phenomenon by holding the moon-pop up high enough to avoid their own shadow. This is a case where Dave made use of knowledge from a previous session. In this case his objective was to have the children avoid a complication and the potential confusion of a second effect that causes a change in the perceived shadowing of the moon.

The moon-pop models, which were used several times, were more effective than the earth-ball models in helping the children see how the phases depended on the relative position of the earth, moon, and sun. Surprisingly, however, several of the children who appeared to have gained an understanding of the moon's phases did not find the models to have explanatory power.

As noted in the story that opened this chapter, I first realized that some of the children saw the moon-pops as capturing only the appearance, and not the cause, of the phases during my interview with Mara at the end of the year. Mara saw the model as reproducing the appearance of the moon's phases. She did not see it as an explanatory model, or realize that the appearance of the phases occurs because the projector, moon-pop, and person form a miniature model of the sun, moon, and earth system.

In subsequent interviews, I probed other children to find out if they shared this view of the moon-pops. For some, the model seemed to have provided a satisfactory explanation. "Well," Sandra explained, "I think that [the point of the moon-pops] was to see the phases of the moon, and, um ... to see how the phases of the moon change."

> Sandra: Like, I didn't really understand it before. I mean, I had learned it a lot, I mean people had told me a lot, but I hadn't really understood it, but when I got the moon-pops, I could experiment with it and see for myself why there are different phases of the moon, and why it's not always like a crescent moon or always a full moon.

Sandra claimed that the moon-pops clarified the phases for her, and she appeared to have an accurate understanding of their progression. Like Mara, however, other children — who were also able to draw the phases — did not believe that the moon-pops explained why they happened. Jerry, for example, said he was thrilled to observe the movement of the shadow across the moon-pop. Nevertheless, he commented that "it really just shows what [the phases] look like, rather than explaining *why* there are phases." Similarly, Emily said that her moon-pop made the topic "less confusing than before, but it didn't really solve my questions ... you know, what, exactly, is it that makes the phases of the moon happen?"

Like Mara, these children seemed to believe that the moon-pops were more of a trick than a real explanation.

Discussion

The children's thinking and activities will be discussed from four perspectives, each of which includes both the model and the model user. These include: ready-made models and models in the making; constructionism; surface and explanatory models; and the degree of "connectedness" between the model and the model user.

Models in the Making Versus Ready-Made Models

Dave's Moon Curriculum and the Context of Model Use

Dave's moon curriculum offered the children a variety of experiences with models. Examples of models in the making included the dramatization of the yearly cycle, the mosquito-bat model, and the animations drawn by the children at the end of the year. In contrast, the scale model of the earth and moon was a "ready-made" model that provoked discussion.

The earth-ball and the moon-pops occupy a middle-ground, which highlights the importance of the context of model use, as well as the role of the model user. Dave supplied the materials for the models and had a clear idea about how the materials might be used. However, his instructions gave the children considerable leeway in how they used the materials, and did not provide explicit guidelines for what to do with them. When he introduced the earth-balls, for example, he stressed that the children were to create their own models, and that they were free to use other materials as well; if they preferred they could create a two-dimensional model on paper. Dave's approach, therefore, was quite different from one that prescribes the materials, details the steps to be followed, and has a single correct result. Given this flexibility, the children can be viewed as significant co-constructors of the models they built.

The way the moon-pop models were used incorporated more elements typical of ready-made model use than was the case for the earth-ball model. Dave was much more explicit in his directions to the students. He told them how far away to locate the moon-pops, and how to achieve the effect of the moon's rotation. The children were given explicit instructions to hold the moon-pops high enough to avoid the earth's shadow. In addition to choreographing their physical motions, Dave directed their initial observational activity. For example, he told them to look carefully at the pattern of light and dark on the moon-pop and to draw the moon-pop in eight specified positions.

Despite these constraints, there were elements in the use of the moon-pop that were characteristic of models in the making. The key to such elements was that the children's primary task was to construct an understanding of the phases of the moon that was satisfactory to them. Furthermore, the moon-pop model was part of an iterative design process, and was introduced in response to issues raised by the children's experience with the earth-ball model.

The models-in-the-making elements of Dave's use of the earth-ball and moon-pop models can be highlighted by contrast with the ready-made model approach of a high school teacher who appears in the film, "A Private Universe" (Sadler, 1988). She used a commercial model with a yellow sun at the center, and an earth and moon mounted on movable metal arms. Half of the moon was painted black, representing the shadowed portion of the moon. The model was prefabricated and clearly designed for instructional use. Because the distance between the moon and earth, and earth and sun were fixed, the model allowed less room for exploration than the earth-ball and moon-pop models.[5]

The teacher showed the children how the model worked, and then called on them to answer specific questions about the moon's phases. The children, therefore, had no opportunity to explore with the model on their own. This highlights the contrast between this teacher's emphasis, which was teaching her students the causes of the moon's phases, and Dave's goal of facilitating the children's exploration. In contrast to Dave, therefore,

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[5]Had the model used light from its sun to generate the shading rather than having the moon colored half black and half white, it might also have also suggested that the phases were caused by the earth's shadow, as happened with the earth-ball model.

who provided his students with materials and some instructions and gave them the opportunity to construct their own explanation of the moon's phases, this teacher used her model largely as a visual aid to reinforce the standard explanation of the phases.

Constructionism and Model Building

Model building is a constructionist activity, and as such offers benefits (noted in the literature review), which include: making details explicit, engaging the children, bringing in their own understanding, and, because of its public nature, encouraging feedback from others. These points will be illustrated in examples from the children's explorations.

Constructing something, such as a model, requires making details explicit. It may provide an opportunity to express something one already knows, or to learn that one knows something by bringing it to the surface; constructors may also be spurred to generate new ideas. For example, in the dramatization model most children drew on the ideas they had learned previously, such as the fact that the moon orbits the earth and the earth orbits the sun.

Children may generate ideas which are not previously held beliefs, as may have been the case with Mariem's portrayal of a rotating sun. Rather, they are motivated by other knowledge, such as the rotation of the earth. Another challenge and opportunity presented by model-making is the need to coordinate bits of understanding that may have been separate before. For example, it was clear to Lara that the relationship of the moon to the earth was parallel to that between the earth and sun.[6] In contrast, Mary appeared to have difficulty imagining the simultaneous relationship between the relative motion of the earth and the sun and that between the moon and the earth.

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[6] Some children may have over-generalized this idea. During the final interviews, I asked a number of children whether the part of the moon's surface that we see changes or remains the same. All of them, including Jerry, who had the clearest understanding of the phases, said that because of the moon's rotation, we see a different part from day to day. Had they made careful observations, they could have seen that the patterns of light and dark on the moon remain essentially unchanged. (This happens because the period of the moon's rotation on its axis is essentially the same as its period of revolution around the earth).

Conscious involvement in construction enables children to bring their own understanding to the task at hand. Dave encouraged this involvement by suggesting that the children give serious thought to the ideas and suggestions of all the children, including those whom they would not usually consider experts. He told them that the experiences of previous classes indicated that everyone might have something important to contribute. One reason that constructionist activities give a diverse group of children an opportunity contribute is that they can incorporate their knowledge and life experience from non-school contexts. For example, Jerry's mosquito-bat model reflected his ability to employ his knowledge of water, baseball, and mosquitoes to build an understanding of eclipses. Larry, the first child to appreciate Jerry's model, was rarely a voluntary contributor to class discussions, but the mosquito-bat model connected to his experience of the world.

When constructions are public, they can elicit feedback. In collaborative work, feedback may come initially from fellow group members. For example, Lara disagreed with Mary's idea that the moon does not move, initially prompting Mary to defend her idea. Similarly, when the groups presented their models to the whole class, children from other groups disagreed over issues such as whether the moon circles the earth 365 times in a year.

Because the collaborative construction of models is shared, it provides an opportunity for children to consider the ideas and methods of others as alternatives to their own, or to identify possible flaws in others' thinking. As was noted in other chapters, the latter opportunity is very motivating for some children, and can result in valuable insights.

Another benefit for children as model makers is the opportunity to encounter epistemological issues about the nature of science, such as those associated with Grosslight et al.'s (1991) Levels 2 and 3. For example, they may learn that models have a purpose, such as communicating ideas, or generating explanations. They may become aware that in designing the models, it is necessary to choose which elements are important, and they may discover that they must choose from design alternatives.

Surface and Explanatory Models

Both the case of Mara and that of the historical model developed by Eudoxos and modified by Aristotle can be analyzed in terms of the concepts of surface and explanatory models, and both raise the issue of what constitutes a satisfactory explanation. What constitutes a surface model, and what constitutes an explanatory model depends on the model users' understanding of models, as well as their criteria for a satisfactory explanation. In the historical case, Eudoxos created what Aristotle considered a surface model, which accounted for the appearance of the planets' movement, but did not include a physical mechanism.

All the children were able to use the surface model aspect of the moon-pop curriculum to learn the appearance and sequence of the moon's phases. Some children also experienced it as an explanatory model. The moon-pop model was not explanatory for Mara, but her recognition and acknowledgment of this fact demonstrates insight into her own process of learning.

As noted earlier, one reason children may frequently interpret models as surface models is that they have significant experience with surface models (more experience with surface models than with explanatory models), such as dolls, model airplanes, and educational toys such as the "Visible Man" and the "Visible Woman." Even the Sundial program, which they may not have thought of as a model, was used as a surface model. Because Sundial was a black box for them, they could successfully use the program to produce data, without needing to understand how it computed the sun's location.

Connectedness

The final feature of the relationships between models and model users that will be discussed here is the degree of connectedness between the model user and the model. This point of view emphasizes the importance for model users of building connections between their thinking and activities with a model, and their other knowledge and experience. Elements that may facilitate connectedness that were mentioned in the literature review and will be used here include: mapping onto a more tangible phenomenon; identifying as a participant in the situation being analyzed; imagining a phenomenon a dynamic, rather than static; mentally exaggerating the scale of some elements of a situation; and analyzing specific cases in detail first.

This section will analyze some of the features of the mosquito-bat model, as well as an idea proposed by Lara to explore the role of connectedness in contributing to the effectiveness of a model.

Connectedness and the Mosquito-Bat Model

The mosquito-bat model is an example of a model that connected to many children's personal knowledge and experience. One strength of the model is that it creates a very tangible image. By replacing light impinging on a ball with water from a balloon bursting on a bat, the active role of the earth as a blocking entity is emphasized. Similarly, the water hitting the mosquito is more palpable (and more obviously consequential) than light hitting a tennis ball.

The mosquito may also encourage a sense of identification — one might identify with a mosquito trying to evade the water, or as someone trying to eliminate a pesky mosquito. This identification process contrasts with the commonly held view of science as distancing and objective. As Evelyn Fox Keller (1983; 1985) and others have argued, scientists such as McClintock and Einstein have used identification with a phenomenon as a way of gaining deeper insight into it.

Viewing something as a process rather than a thing may make it more understandable, perhaps because the interrelatedness or interaction between the parts is brought to life. The image of a bursting water balloon is a dynamic one. The water moves forward and either hits the mosquito or misses it. This may make it come to life more dramatically than a static diagram or a static three-dimensional model of the earth, moon, and sun.

When a feature of a model is exaggerated — i.e., changed in size or made more or less prominent — it may aid understanding. This exaggeration may make it clear why a feature is important or unimportant, or the change may provoke a more flexible and productive way of thinking about the phenomenon. For example, the difficulty in understanding that was resolved by the mosquito-bat model was how a partial eclipse could occur. Perhaps the child who brought in the question could only think of the moon as being above, below, or within the shadow (perhaps he was not visualizing these as actual positions, but mutually distant, but vague, locations). The small size of the mosquito, as well as its mobility, might have encouraged visualizing it in a variety of safe positions, not only points in the middle of the air pocket (i.e., points on the earth's orbital plane). For example, if a mosquito near the danger zone (i.e., the watery edge of the "shadow") is visualized as the center point for a moon of sufficiently large radius, one could see that only part of it would not be directly hit by the water. This would correspond to a partial eclipse.

<u>Lara's Idea of Making a Model of the Quarter Moon</u>

During her year-end interview Lara commented that the moon-pops activity was "O.K.," but complained half the time they sat and had discussions. She suggested that "it would have been more fun if we got to build models of what we were doing." For example, they could work in their groups to figure out "where the moon will be so that it will be exactly a quarter, and then we will have to build the earth and make it into a model."[7] On the surface, it might seem that constructing a static model to show the position of the quarter moon might be less challenging and less effective as a learning experience than making a dynamic model (such as an earth-ball or a moon-pop) that incorporates the moon's motion and phases. However, the following analysis suggests why this might not be the case.

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[7]She later made it clear that she basically thought of model building as a physical construction when she said that "[If] Dave asked us to build a model or something, then that probably would have been more interesting, because of being able to work with your hands and work with materials."

A problem that arises for some children is that although they may develop an understanding that the phases depend on the position of the moon relative to the earth and sun, they may not construct a clear understanding of the correspondence between the two. This was articulated by Heather, a high school student interviewed in "A Private Universe." She drew a picture with a sun, an earth, and a circle around the earth to show the moon's orbit, and she endeavored to explain the causes of the seasons.

> Um, well we learned the phases of the moon, although we didn't learn where the moon was at those times. At least *I* don't remember learning that. That makes it sort of hard because you know *what* the phases are, but you don't know where the moon was. I mean the moon could be over here, it could be over here, it could be over here, it could be over here. [She points to different spots on the orbit.] It could be practically anywhere on its orbit around.

In building a model for a particular phase, such as the quarter moon, the children would have to explicitly construct a correspondence.

Conclusion

In examining the children's creation and interpretation of models we can, as in previous chapters, identify seeds of mature science practice in the children's thinking and activities. This was most vividly illustrated by the story of the mosquito-bat model. Several of Jerry's classmates used it as an explanatory model to raise and discuss questions concerning eclipses on other planets. Such examples emphasize the similarities between the science practice of children and scientists.

In contrast, Mara's question about the moon's phases illustrated the significant differences that can arise between children's and professional scientists' interpretations of models. Mara did not have certain knowledge that is usually implicit or tacit for experienced model users, which would have enabled her to understand the explanatory power of the moon-pop model. Furthermore, this story shows how a child's presentation of an apparently satisfactory explanation can mask both significant limitations in her understanding, as well as her own desire to understand the phenomenon more deeply.

Chapter 7: Conclusions

In this final chapter I review the contribution of the dissertation, make recommendations to educators, and suggest directions for future research.

Summary of Contributions

The major contribution of the dissertation is the framework I have developed for analyzing children's science thinking and activities. The focus of the analysis is the identification of the seeds of science practice that are present in children's inquiry.

In summary, this framework involves:

- The identification of the seeds of children's science practice, which are activities that bear resemblance to those of professional scientists, both in the processes involved and the challenges faced.
- The identification of specific themes that were productive for analyzing the science thinking and activities of this group of sixth graders: science in the making, background influences, contradictions, and groups. These themes also highlight aspects of the practice of science that are largely absent in elementary school science.
- The identification of specific activities that are seeds of science practice, along with concepts useful for analyzing them:

generating questions —	the value of questions involving contradictions
	use of background influences to interpret questions
constructing definitions —	delimiting the scope of a term
	creating operational definitions
creating and using models —	ready-made models and models in the making
	surface and explanatory models
	tacit knowledge

- Ideas for improving science learning that are informed by the seeds of science framework.

The Themes

In this dissertation I identified four themes as lenses for focusing on the children's thinking and activities: science in the making; the role of background influences; the identification of contradictions; and the role of groups. These themes are valuable for gaining insight into the children's inquiry process because they apply not only to the children but also to professional scientists, This was illustrated by the episodes from the history of science.

The focus provided by these themes differs from that present in most classrooms and in much science education research. For example, the focus in the dissertation is on science in the making, rather than on ready-made science. This theme is quite different from the focus on specific science content knowledge (e.g., Carey, 1985), or on the way that knowledge is structured (e.g., Chi, Glaser, & Rees, 1982; Larkin, 1983), which necessarily highlight the children's limitations vis-a-vis scientists. It emphasizes the importance of paying attention to the process of investigation, and not only to the results, because scientists generally have greater relevant knowledge and experience which may lead them to more successful outcomes. In addition, a focus on science in the making draws our attention to aspects of the exploration process that are least routine, and therefore showcases the capacity of both children and scientists to solve novel problems.

Another way the themes can help us is by highlighting aspects of the children's experience and process that are analogous to those important to professional scientists. This is clearly illustrated by the theme of *background influences,* which play a role for the children similar to that played by theory for scientists. The analysis of the learning stories showed that background influences can serve as interpretive frameworks through which children perceive situations and which inform their responses. This common ground was highlighted by analyzing the questions and the process of constructing definitions of both historical scientists and of children. Again, the learning stories illustrated the way in which paying attention to relevant background influences (including tacit knowledge) helps us understand children's inquiry process.

An important feature of the theme of *contradictions* is that it focuses our attention on one of children's strengths: by the time they are in late elementary school, children are highly skilled at identifying contradictions in the ideas of others, and they enjoy doing so immensely. As is the case in professional science, these challenges are a critical part of their science process; they either promote the further development of ideas, or identify weaknesses that cause them to be revised or dropped altogether. In either case, this contributes to the on-going development of science.

The role of the group, which is of key importance in the professional practice of science, provides another shift in focus, since school settings tend to emphasize the performance of individual children, while historians and philosophers of science take into account a context of communities of researchers who share certain theories, methods and ontological commitments (Kuhn, 1970; Lakatos, 1970). Therefore it is important to consider the ideas and actions of groups of children, and not just individual performances.

The Activities

This section summarizes some of the major points I made in focusing on the activities: generating questions, constructing definitions, and creating and interpreting models.

Questions

Children's curiosity and ability to generate questions has been long noted and put to use by progressive educators. In this chapter, attention was paid to a specific type of question: that which involves the recognition of a contradiction. A notable feature of these questions is that they require the coordination of two seemingly discrepant observations or beliefs. Since scientists try to construct comprehensive and consistent explanations of the world, this effort to resolve contradictions is of great importance in science.

The chapter also emphasized the theory-like role that background experiences play in generating these questions. This was made evident by the fact that some of the children's questions were initially obscure, but became intelligible when the children's background influences were taken into account. Therefore, by paying attention to background influences teachers can better understand children's questions and the ways they are thinking about science, as will be further discussed in the section on recommendations.

Constructing Definitions

In almost all experiments and inquiry activities designed for children, the quantities to be measured, compared, and otherwise manipulated are expressed in terms that have been well defined. In chapter 5, I gave several reasons why this is an unfortunate limitation. First, the process of constructing definitions can lead children to a deeper understanding of the phenomenon being defined and the topic they are studying. It can also spark and hold their interest more strongly than a situation in which terms are already defined. In addition, when children's experience with definitions is limited to those that have been previously constructed, they are deprived of an important opportunity to learn about the nature of science. As illustrated through the history of defining and treating syphilis, and the experimental debate over spontaneous generation, the process of constructing definitions is key to the process and progress of professional science.

Models

Models have been the subject of extensive research and educational intervention. The analysis in chapter 6 offered a novel look at the way children use and understand models. One point made was the extent to which the models are "ready-made" versus "in the making." As shown by the analysis of the "earth-ball" and "moon-pop" models of the phases of the moon (for which the teacher provided instructions of varying detail), this was seen to be not only a function of the materials used, but also the degree to which the children were co-constructors of the models.

A second perspective developed in the chapter is the distinction between surface and explanatory models. The story of Mara — who found that, for her, a model showed what the phases of the moon *look like,* but not *why* they happen — highlighted the importance of tacit knowledge. Such knowledge may be taken for granted by experienced model users, but may not be part of the understanding of those with less experience. How such tacit knowledge may be acquired will be addressed in the section on recommendations.

The framework of constructionism was used to identify and explore benefits of the children's model building activities, which included: making details explicit, engaging the children, bringing in their own understanding, and, by virtue of the public nature of models, encouraging feedback from others. The mosquito-bat model, which was spontaneously developed by one of the children, is an example of a model that was easily appropriated. The children were able to connect imaginatively to the image of a mosquito who either successfully hides from, or is alternatively drenched by, the "water" of the sun's light.

Recommendations

This research was motivated by my desire to support children's engagement in science inquiry and learning. The recommendations, therefore, are directed towards that goal. The presentation here is brief because although these recommendations are based on the framework I developed in conducting the research, implementation (and hence empirical testing of these ideas) is a direction for future research.

I have chosen to frame these recommendations for teachers because they work closely with children. However, the ideas developed in this thesis are also applicable to educational policy.

In brief, the recommendations are that teachers should:

- Offer children opportunities to engage in science inquiry that is rich in challenges of the type elaborated upon in the learning stories. For example, children should have the chance to construct definitions relevant to their inquiry.
- Make an effort to understand and interpret the children's thinking and activities, in order to better support their science inquiry.
- Use the framework of seeds of science practice and the themes and activities discussed in the dissertation as an aid to making sense of the children's science explorations.
- Develop their understanding of this framework, in part, by applying it to their own activities and explorations.
- Make use of their own ideas, experiences, and strengths in putting these ideas to work in their classrooms.

Directions for Future Research

The work in this dissertation suggests several directions for further research: an augmentation of the framework to include additional themes and activities; further exploration of questions that arose in the course of the study; and a comparable study of children in a different setting. Most importantly, the framework should be put to use in a classroom setting to determine the extent to which it helps teachers create rich science learning environments.

The data collected during this research project provides several additional themes and activities, which can be used to expand the existing framework. For example, a theme touched on in both the discussions of models and the construction of definitions is the role of *iterative processes* in science research. The role of feedback, which may take the form of experimental results or of a research community in which one participates, presents another important theme that should be further explored. Many specific findings in science are eventually superseded, or at least found to be accurate in a more limited domain than was originally believed. The value of partial or incomplete results, which was also reflected in the data, is another theme that might expand the framework. Hammer (1995) notes that it is not easy for teachers to focus on what is most valuable in children's participation in science because it is often overshadowed by the flaws in their conclusions. The theme of partial or incomplete results can be used to help teachers refocus their attention on the positive features of children's explorations.

The three activities that were the focus of this study of children's seeds of science practice were not the only ones that recurred in the children's science exploration. Additional activities illustrated by learning stories that were not incorporated into the dissertation include: the children's formulation of problems, their creation and use of representations, and the ways in which they analyze data.

Another direction for future research is to explore questions raised by the current study. One such question involves the way in which children functioned as a group.

I propose that it may be useful at times to consider how the children collectively act more like a single scientist than like a group of scientists. This idea is based on the observation that the children were able to recognize weaknesses in the arguments of others that they did not recognize in their own thinking. Thus, the recognition of significant relevant facts, logical flaws and alternative explanations, which are internal processes for a professional scientist, could occur externally for children in a group. This is in keeping with Vygotsky's idea that "an interpersonal process is transformed into an intrapersonal one" (Vygotsky, 1978, p. 57). Other functions that may be served by children in the group, or by an adult facilitator, are: returning the focus of attention to the idea of central importance, identifying an important sub-problem, and synthesizing or reconciling two ideas. Making this issue the explicit focus of in-class research would allow for elaboration of these ideas.

One of the findings that was most surprising to me was what I characterized in chapter 6 as Mara's interpretation of the moon-pops as a surface model. I only had the opportunity to explore this issue with a few of the children, because it arose during the final interviews. Because the way in which tacit knowledge affects children's learning is central to the success of science education, it is important to explore this topic in the context of other settings that involve models. Under what conditions would other children share these ideas?

This dissertation is an analysis of a particular group of sixth-grade children conducting science inquiry in particular learning environments. In writing the learning stories I have tried to include enough details to give a sense of both the children and the activities. A study of a different population of children, in a different setting, would help to further articulate the kinds of seeds of science practice one can find in children's science inquiry, and the features of the learning environment that can inhibit or help foster them.

Again, the framework presented in the dissertation is proposed as a tool to aid the process of understanding children's science activity and fostering their science inquiry. A central direction for future research, therefore, is to find out if teachers find this framework helpful. Does it promote their own understanding of science, increase their willingness and ability to undertake science investigations of their own, and ultimately help them to support children's science inquiry?

Final Comment

Children bring a wide range of skills to science inquiry. The goal of this dissertation has been to uncover positive aspects of children's thinking and activities that could easily go unnoticed. My hope is that the ideas presented here will prove useful to teachers and educational researchers who are working to support children's science exploration.

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