Learning Science
A Singular Plural Perspective
NEW DIRECTIONS IN MATHEMATICS AND SCIENCE EDUCATION
Volume 1

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Scope
Mathematics and science education are in a state of change. Received models of teaching, curriculum, and researching in the two fields are adopting and developing new ways of thinking about how people of all ages know, learn, and develop. The recent literature in both fields includes contributions focusing on issues and using theoretical frames that were unthinkable a decade ago. For example, we see an increase in the use of conceptual and methodological tools from anthropology and semiotics to understand how different forms of knowledge are interconnected, how students learn, how textbooks are written, etcetera. Science and mathematics educators also have turned to issues such as identity and emotion as salient to the way in which people of all ages display and develop knowledge and skills. And they use dialectical or phenomenological approaches to answer ever arising questions about learning and development in science and mathematics.

The purpose of this series is to encourage the publication of books that are close to the cutting edge of both fields. The series aims at becoming a leader in providing refreshing and bold new work—rather than out-of-date reproductions of past states of the art—shaping both fields more than reproducing them, thereby closing the traditional gap that exists between journal articles and books in terms of their salience about what is new. The series is intended not only to foster books concerned with knowing, learning, and teaching in school but also with doing and learning mathematics and science across the whole lifespan (e.g., science in kindergarten; mathematics at work); and it is to be a vehicle for publishing books that fall between the two domains—such as when scientists learn about graphs and graphing as part of their work.
Learning Science

A Singular Plural Perspective

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PREFACE

Every book is the result of a historical process that authors both produce and are subjected to. This is also the case for this book, which has long been coming. Or, to express it differently, I have wanted to write this book for a long time, ever since I engaged in extended investigations aimed at better understanding what it means to learn from the perspective of the learner. For a considerable time now, I have had a sense that the fundamental problem of learning theories is their failure to explain why I do one thing rather than another and how learning arises from my engagement with the world in the way it is given to me rather than to someone else. For reasons that I exemplify, discuss, and theorize in the course of the book—especially in chapter 3—learners forget characteristic aspects of the learning process at the moment they come to know. This may not be a problem generally, but it becomes a problem when these learners become teachers: unless they remember what it means not to know and about the aporia of learning, they expect from their students the impossible: to intend the unknown learning object. There is a process of amnesia, whereby the newfound understanding obliterates how human beings perceived and understood the world just minutes before their new knowledge has taken hold. Although I began to become aware of the problems most theories have in describing learning from the perspective of the learner in 1995 during two extended research stays abroad, I never found the time to investigate the relevant issues in depth.

In 1999, following an invitation that Manuela Welzel and Stefan von Aufschnaiter (then at the University of Bremen) extended to me, accompanied by a successful application to the section cognitive neurosciences of the Hanse Institute for Advanced Studies, Delmenhorst, I decided to spend three months in that part of northern Germany where the Institute and the university are located. Manuela provided me with access to an extended database featuring tenth-grade students in the process of learning (about) static electricity in a class that she and Stefan had co-taught. My explicit goal was to take a first-person perspective on learning. I was reading Maurice Merleau-Ponty’s book on the phenomenology of perception at the time and had long been interested in Martin Heidegger’s work on how the world is experienced during everyday activity (Being and Time).

Every day at the Institute, I watched the videotapes, attempting to understand how these students perceived the world, why they were doing what they were doing, and how to infer from their conversations and actions just what it was they attended to, which things in the setting they were conscious of, and which things they took for granted without consciously being aware of these. To support my interpretive work, I had requested from Manuela the curriculum materials that she
had used with the students. So from early on, the desk in my apartment at the Institute was littered not only with the normal implements of research—books, videotapes, computer, and transcripts—but also with the materials that I could use to produce and reproduce electrostatic phenomena.

It was while I attempted to reproduce something I was seeing students do that I noticed myself perceiving or not perceiving in the same way students did. For example, it was after watching one of the teachers interact with students about testing static electricity that I began to notice the fact that the lamp I was using was glowing differently depending on the materials I was using at the moment. That is, much like the students I had not attended to the fact that the lamp reacted differently when testing positive versus negative charges. This realization hit home hard. If I—a trained physicist with a masters degree and with a good part of the coursework toward a Ph.D. in physical chemistry—do not see something that is crucial for understanding a physical phenomenon and therefore do not act toward or use as resource in my own thinking some specific feature that the teachers take for granted and as shared, how much more difficult must be the situation for the students with considerably less experience? At the time, this realization provides me with the impetus to engage in an extended study of learning from a first-person perspective. In this endeavor, I am not interested in the traditional lore of scientific concepts and conceptual change or (radical, social) constructivism—from experience I know that these theories do not work well when I try to understand learning in real time, real contexts, surrounded by real people. Rather, I decide at the time to experience knowing from a learner perspective and to re-experience what it means to learn in a domain that I do not know; and I decide to do this in the most rigorous way. As a trained physicist, however, there is a possible danger that I am already looking with a conditioned lens, though there are many situations where I act just like the students I observe, that is, in terms of a discourse of negativity that many in the discipline of science education use.

For this reason, I decided to engage also in an extended inquiry of my own learning, taking note of events whenever it strikes me that I have learned something about learning. In one case, I decide to take a bicycle ride along an unfamiliar route (unfamiliar at least the first time) for number of times, which turns out to be twenty days in a row, and to note everything that I came to know, remember, anticipate, and so forth.

In this way, I created a large database of original observations and interpretations in the course of my stay at the Institute and following the stay to this day. However, even during my stay I got sidetracked with an emerging interest concerning gestures, which pre-occupied me over the next several years and let me come to understand how gestures function as a communicative precursor of verbal scientific language. In fact, today I know that these studies have not been on a sidetrack at all but central to my present-day understanding of how human beings come to know. Gestures are central to my ways of taking up position in the world and they, just as my actions, directly connect me with my environment. They are central to understanding why my everyday actions, including thinking and communication, are so efficient: I do not have to make present again the things I am connected to,
as long as I can expect to be connected to the world and the situations I find myself in. I do not need to memorize the functions and pull-down windows on my computers, because I know that I can find these windows and their contents whenever I need them. I know that I have not memorized them as soon as someone asks me how to do something on the computer when there is none present. I cannot respond and will seek a computer to show the person how to do what he or she is asking me about. But this case is not interesting, as my knowing always is relevant only in specific settings. Incidentally, however, science educators and science teachers have students to do a variety of things disconnected from any relevant context that everybody else uses and under almost every other situation that is relevant. There always are resources that I can draw on to accomplish my goals.

Since my stay at the Institute, I have also become deeply familiar with dialectical theories of activity, such as those that are framed in terms of an agency|structure dialectic (e.g., Sewell, 1992) or as a cultural-historical activity theory (Leont’ev, 1978). Dialectical theories have their origin in a lineage of philosophical and social psychological work that began with Georg W.F. Hegel and Karl Marx and subsequently has become central to the sociocultural and cultural-historical schools of Soviet psychologists, most notably Lev Vygotsky and his student Alexei Leont’ev. Klaus Holzkamp, a German Critical Psychologist, has taken this latter person’s theory furthest in his own work on learning from a subject’s perspective, resulting in what he calls Subjektwissenschaft, science of the subject.

After having written a section in my Doing Qualitative Research: Praxis of Method (Roth, 2005a) about how to do cognitive phenomenology, I have felt ready and in the position to tackle the contents of the present book. I can now say that although the book has long been coming, the intervening years have been important for my own learning about learning and for developing suitable theoretical resources that today allow me to think about the aporias of learning. It turns out that I also have become familiar with an area of continental philosophy that has taken its leads both from dialectics and phenomenology, overcoming the weaknesses of both. The philosophers include Jacques Derrida, Paul Ricoeur, Emmanuel Levinas, Jean-Luc Nancy, and Didier Franck. Through reading these philosophers, I have been able to integrate many heretofore-separate domains in my understanding.

A book such as the present does not emerge from thin air but is itself the result of a historical process that includes writing in general. Other pieces of writing with direct relevance to one or the other chapter often precede a book, though they may have undergone substantial transformation, sometimes required by the new context in which they appear. This also is the case here. I have written about student learning from a phenomenological perspective: Two articles on the topic, which appeared in Learning and Instruction (Roth, McRobbie, Lucas, & Boutonné, 1997a) and the Journal of Research in Science Teaching (Roth, McRobbie, Lucas, & Boutonné, 1997b) have been integrated into chapters 1 and 2, respectively, because they constituted the starting point for the present inquiry. Some of the material on perception in chapters 3 and 4 has figured in an article on the phenomenology of perception that has been published by the editors of FQS: Forum Qualitative Sozi-
However, the context for the data—and therefore my arguments generally—has changed substantially: context, data, and arguments have become an integral aspect of a more general, dialectical theory of culture, knowing, and learning. Aspects of chapter 7 and 9 have been developed and used in an article that was published by *Cognition & Pragmatics*. The ideas articulated in chapters 6 and 7 have their origin in a variety of papers normally using very different data, published in *Discourse Processes, Journal of Pragmatics, Learning and Instruction, Language in Society, Science Education, Journal of Research in Science Education*, and *Semiotica*.

A project such as this never succeeds without the support of those close to the author, the agencies that provide grants, the institutions that give authors leave, and everybody else who contributes to making society what it is and thereby provides the author with the space to do research and write books. But there are also some organizations and individuals who contribute more directly and immediately to making a project possible; and I want to thank those specifically relevant to my work on the current book. The first two chapters derive from data that I collected together with Cam McRobbie, Keith Lucas, and Sylvie Boutonné in a high school in Brisbane, Australia, supported both by the Center for Science and Mathematics Education at Queensland University of Technology and by the Social Sciences and Humanities Research Council of Canada. I am grateful to the teacher and students, who willingly hosted us. I am particularly grateful to Manuela Welzel (University of Education, Heidelberg, Germany) and Stefan von Aufschnaiter (professor emeritus, University of Bremen) for their generosity of hosting me. They have provided me with the required connection to receive the funding from the Hanse Institute of Advanced Studies and who provided me with access to the videotapes of the physics course they had taught and for the extensive discussions they engaged me in concerning knowing and learning. These discussions allowed me to evolve a better understanding especially because both Manuela and Stefan and their graduate students were taking a perspective on knowing and learning that differed from my own. My thanks go to Gerhard Roth, the director of the Hanse Institute, which funded my stay and provided for an opportunity to do nothing but research in an environment conducive to research and writing. Finally and most importantly, I thank my wife Sylvie Boutonné for her continued support, which allows me to engage in such time consuming efforts as writing books.

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INTRODUCTION

TOWARD A SINGULAR PLURAL PERSPECTIVE ON SCIENCE LEARNING

The natural sciences have a strong experimental character. In schools, this aspect of science is reflected in laboratory work. It therefore comes as no surprise that for a long time now science educators have suggested that there are many benefits from using laboratory activities as part of instruction. Traditionally, this laboratory work consists of exercises in which students verify textbook equations or are asked to observe phenomena relevant to their current topic of study. These laboratory exercises generally are well planned ahead of time and students usually are given step-by-step instructions. Although there is a sense that understanding science and about science requires understanding its experimental nature, many questions have been raised about the real benefits of laboratory investigations to students’ scientific understanding. All too often, teachers find that their students do not learn or come to understand the science in intended ways—leading them to use laboratory tasks only as ancillary activities and frequently to introduce some “fun” into the subject.

A central reason for engaging in laboratory tasks is to prepare and see in action phenomena that otherwise may not exist or may not be accessible but that nevertheless are the phenomena as theorized in science. That is, science teachers frequently ask students to conduct laboratory activities designed to show specific scientific principles in action. However, there are some problems with this practice. It is widely accepted that all observation is interpretation. This contention, initially brought forth on philosophical grounds, has recently found support in research on the physiology of perception and on the interaction of discursive practices and “seeing.” Because interpretation arises from the interplay of existing understandings and experienced world, what I observe depends on what I already know. This means that students who do not yet know the scientific principles associated with a particular laboratory experiment or demonstration probably will not see just what their investigation is to show, for the very principles (laws, concepts, theories) that are to be exhibited are prerequisite to seeing the phenomenon. As a result, students perceive different worlds than teachers, making science learning through discovery next to impossible. It does not surprise then that many science teachers do not trust learning through laboratory activities and prefer to stick to lecturing, doing word problems, and teaching how to respond to questions about concepts on exams (“teaching to exams”).

Despite the shortcomings of laboratory tasks, teachers still use them; some even use it in the discovery mode. Discovery learning, which had its heydays during the 1960s and 70s, still underlies much of students’ practical activities in school sci-
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ence and mathematics. When students do more open ended laboratories, the learning situation is exacerbated in that scientific phenomena require not only observation but also the preparation of materials; that is, embodied laboratory skills are prerequisite to setting up nature in such a way that it exhibits the phenomena of interest to scientists. This leads to two sources of problems why students do not make the observations, or discoveries, that teachers—working from a traditional paradigm—want them to make. First, because of their different theoretical lenses, students are likely to perceive and interpret any situation differently than their teachers do. Second, because of their different competencies in laboratory practices, students frequently prepare events that, do not illustrate the concepts at hand even within the teacher’s framework; that is, there is a gap between the instructions students receive for doing the investigations and what they actually enact when they manipulate the materials.

Few studies in science education have investigated at a micro-level and in a minute-by-minute fashion what students do and learn through traditional laboratory exercises in science. But there are some indications that students learn to follow instructions rather than developing a scientific understanding of the observed phenomena (Amerine & Bilmes, 1990). One sociological study showed that doing an experiment successfully according to the instructions given by another person is not a self-evident event but requires considerable situated interpretation. In that study, a sociology student volunteered to execute the instructions of a quadriplegic student enrolled in a chemistry course (Lynch, Livingston, & Garfinkel, 1983). The authors suggest that the relationship between instructions and students’ actions is quite precarious and ambiguous. While indispensable for the students, the adequacy of formal instructions cannot be determined through reading them:

These written instructions were simply not adequately descriptive of the work of doing an experiment since they omitted the embodied engagement of the students with the table-equipment. And since the students did not yet know these embodied practices, it was up to them to discover them. (p. 211)

The cited study has been conducted within an ethnomethodological framework. In the science education literature, however, assumptions about laboratory work remain largely unexamined. There are studies indicating that laboratory activities are largely auxiliary and, from the teachers’ perspectives largely dispensable aspects of science classes; but fine-grained analyses of traditional laboratory work are lacking. There are no empirical studies that show how doing something with the hand brings about conceptual and discursive practices, for example, how opening and closing the tap on a burette leads to an understanding of acid–base titrations and how to write balanced chemical equations for these. Therefore, definitive answers to questions about the pedagogic value of laboratory work are unlikely to exist until the moment when science educators focus on what students actually do in the laboratory tasks that they are assigned to do. This requires researchers to study why students do what they do, based on what they actually perceive as objects in and opportunities for action.
Claims about the value of laboratory activities are largely unexamined and constitute a powerful, myth-making rhetoric; and school laboratory activities are largely ill-conceived, confused, and unproductive in that many students learn little of or about science and do not engage in doing science at all but take the tasks as a diversion from listening to teacher lectures. To understand why students appear to learn so little from laboratory tasks, researchers need to take the students’ points of view; that is, researchers need to view classroom events from the perspective of someone who does not yet know what he or she is expected to learn and who therefore cannot intentionally learn what it is to be learned. That is, the thing to be learned cannot be the goal of actions or the motive of activity, because in both cases, the object has to be given, which is exactly not the case in learning. What I-student will learn by engaging in some task is beyond the horizon of what I currently know and therefore I cannot intend to know what I am supposed to know through engaging in the task. Yet students are evaluated on what they do in the laboratory, how they do it, and what their outcomes are. Thus, students engage in tasks that they have little control over because they cannot evaluate what they do, yet they are graded in all phases on how well they do what they do. It is not surprising then to have a considerable number of students continually asking, “Am I right so far?”

Students cannot know the object of learning, because it is the intended outcome of the unit of study. Students therefore are better understood as groping in the dark, attempting to bring light to what it is that they are to know; or, to use a different metaphor, students are to be seen as travelers who decide to go beyond the horizons of their familiar territory so that they cannot intentionally go somewhere specific, as they do not know what lies beyond, much like Columbus could not go to a specific place as he did not know what was beyond. But what do I do in such a situation and how do I deal with the aporia that the thing to be learned cannot be intended but has to be welcomed whenever it knocks at my (the learner’s) doors? Taking the learner’s perspective on learning is a methodological move characteristic of phenomenology and first-person approaches in social psychology.

Some of the basic assumptions underlying phenomenological thought that also figure in much of the current work in situated cognition and ethnmethodological analyses of everyday practices are: (a) Beliefs and assumptions implicit in everyday practices cannot all be made explicit and are discursively constituted for the purposes at hand; (b) practical understanding, which is observable in the spontaneous activity of people acting in their everyday worlds, is more fundamental than detached theoretical understanding; (c) my primary relationship to the objects and events of my activities is not through having representations of them; (d) sense is fundamentally social and cannot be reduced to the meaning-giving activity of individual subjects and social activity is the foundation of intelligibility and existence; and (e) in a first-person framework, it makes little sense to speak of things that bear individual properties independently of acts of perception.

In a first-person approach, my world, a world that consists of objects with properties and events, is considered to arise through my involved, purposive, and goal-directed activities. The thinginess of objects and events that are relevant to what I
do emerge from my active engagement with the world as it is given to me in my perception. In many circumstances, I act without a need to represent the context in my mind; I live in a transparent world, where I can take much for granted, where a lot goes without saying, and a world to which I do not have to attend consciously. However, because the verbal articulation of the unspoken is a never-ending process, new articulations and interpretations of an object or event are always possible. Such interpretations are always from within my horizon that is constituted by my past experiences, assumptions implicit in everyday discursive and material practices (“common sense”), and my familiarity with the current situation. For my interpretations to be similar to those of someone else, I have to share with him or her a great deal of this horizon: even an instruction for operating a photocopier can lead to considerably different actions if the operator is a designer of such a machine—and thus a participant in a community with a common worldview—or not. A second important way for aspects and features of things to emerge into my consciousness is when the inconspicuous, unobtrusive and inoffensive nature of my everyday world and its transparency disappear. At this moment, a moment I denote by the term breakdown, objects and events take on properties and aspects.

THE EVERYDAY WORLD

Human beings primarily are embedded in the material world because of their bodies; and because of this, they have a primary contact with this world. My body is body among bodies; as a person, I am person among persons. Being, therefore, is being singular plural (Nancy, 2000), in a material and a social sense. Before the world can be reflected upon, before experiences and different parts of the world can be talked about, human beings always already have gained experience and have developed some knowledge about it through this bodily inclusion in the world. This corporeal experience of the physical and social world cannot be fully recovered in the use of language; it remains implicit in human actions but constitutes a background and horizon that “biases” any future experiences. Reflection and speaking about this embeddedness in the world is always delayed with respect to practical understanding; human beings can never totally explicate what they already have experienced, particularly not in any approximation of a totality.

What I know defines the ground for what I can learn. Given that I—as a concrete realization of general human possibilities and being singular plural—am endowed with common sense because of my participation in society from my very beginning and because of my use of a common language, one critical question is: “How can I know science given that in the final recourse, my ‘prior knowledge’ always is common sense?” That is, science education presupposes that during instruction, I have to appeal to and build on common sense to overcome common sense. That is, common sense constitutes a fundamental lens through which I perceive and act toward the world; what is given to me in perception is not divided into real and “perceived,” but is always real to me. This perceived world is characterized by articulations or segmentations at different levels. The most prominent organizing principles of the commonsense world are parts, wholes, and their rela-
tions, part to part within a single whole, identity, overlapping, and discreteness. Entities are three-dimensional, have two-dimensional closed surfaces, and are attributed qualities (color, temperature, hardness) and properties (mass, weight, size).

Research on the processes involved in learning science seldom if ever focuses on more fundamental questions of how people can learn from their experiences—as distinct from an objective world—and what they learn during this experience of something really new. Science educators and science teachers simply assume that their students encounter a world cut up—i.e., articulated—in particular ways and that they are more or less successful in copying to appropriate the theories human-kind has developed for understanding this world. Rarely does research focus on more basic questions such as what, why, and how students should learn anything from laboratory experiences, and what these experiences are like.

An important aspect of this book therefore deals with the world and things as these are given to students in their perception—mainly touch and sight—and with the fundamental conditions that this provides for their learning of science. I sometimes use the term *ontology*, which denotes a theory or conception of being, that is, the ensemble of things that surround a person, which constitutes the world of my experience, and which I experience as objectively present. Here the pun arising from the double meaning of “objectively” is intended: The objects of my experience truly are objectively present, as objects; these objects, in the way they are present, constitute resources for me to make plans, to formulate goals, and to act. It is only when there is reason to doubt my perception that I begin asking whether there are other ways of looking at the situation. This is the case for entities and processes: Common-sense notions take substances to exist continuously and identically through time, existing in their totality at every moment; processes unfold in time existing at no one moment in time in their totality.

In this book, I use classroom examples where high school students come to experiment with and use simple devices that sometimes are used with much younger and even elementary students. The investigations include simple tubular and solid cylinders and spheres that are made to roll down an inclined plane or they include a variety of materials that are rubbed against each other to create static electricity and subsequently are tested using a glow lamp, Styrofoam ball, or an electroscope. A major question I attempt to answer is, “How do students perceive these materials and devices?” For example, they charge and discharge an electroscope (Figure i.1) in particular ways. I provide answers to questions such as “How do students possibly experience and encounter this instrument?” “What structures do they attend to?” “What whole and part relations do their actions and talk reveal?” The questions are pertinent, as the world is never given to me, the learner, as a whole, but, as shown here, is revealed to me in my making connections between my actions and perceptions. Tools in particular—such as the instruments for detecting static electricity (Figure i.1)—are encountered not as assemblies of material parts, but as integral wholes that are useful because one can do things with them. Thus, in chapter 11 students first encounter the electroscope as a whole, as one connected thing. My case materials exhibit how some plastic insulation between the central suspension and the outer ring comes into being as students engage with the instrument,
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and sometimes only after a teacher asks some questions. Similarly, in chapter 4 I describe and theorize how the different elements of a neon glow lamp (Figure i.1) come into being in the course of students’ extended inquiries and as a result of their need to understand why the lamp does or does not glow—especially in situations where a presumably charged object has been brought close.

In this book, students’ learning is articulated as a positive phenomenon, that is, in its own terms rather than in terms of an external framework in respect to which students’ knowledgeability is judged as deficient and in need to be improved. In a positive perspective, I ask how students’ action possibilities and the worlds given to them in their perception change; in a negative approach, I would make statements about what students do not know and what they do incorrectly. Most current research reports on science learning reads as if students do something wrong within the standard frame intentionally or because of something missing. Instead, I take the position that to understand why students do (“wrong”) what they do I need to understand the world they live in and that is apparent to them in their perception. I assume that at every point, students make the most reasonable decision and take the most reasonable action. Because it is reasonable, all I need to understand what they do is to find out the grounds that allow what they do to be reasonable. If what students do is different from what I might have done, it may be because the world looks different from their position. This position, I take to be constitutive of their dis-position (Nancy, 2000), that is, the position as different from my own. This disposition arises from our being singular plural, that is, body among bodies, which cannot be at the same place at the same time, forcing them to be positioned differently. Because I am dis-positioned, I also make different suppositions and embody different (pre-) suppositions, that is, dispositions. To understand the positions (“where they are”), dispositions (“what the world looks like from there”), and (pre-) suppositions that characterize students in science learning tasks is the principal goal of this book. My own fundamental presupposition is that learners do what they do because it is the most plausible thing to do or because it is the most promising thing to do to expand their action possibilities with respect to realizing the goals of the task they are working on.

Figure i.1. Electroscope (left) and neon glow lamp are instruments used to test for the presence of electrical charges.
TOWARD A SINGULAR PLURAL PERSPECTIVE ON SCIENCE LEARNING

AGENCY|STRUCTURE

Most theories of acting, knowing, and learning are deterministic. It is only within a deterministic approach to science teaching practice that curriculum objectives—often stated in terms such as, *At the end of this lesson, students will know [be able to] . . .*—make any sense at all. Wherein theories differ is the source of the forces or causes. In psychological theories, including (radical, social) constructivism, the causes for our actions are located in the individual—in the epilogue I articulate reasons why (radical, social) constructivism certainly is a wrong theory of learning, one that is internally contradictory and inconsistent. Thus, for example, young students are said to say that the earth is flat *because* they “have” a “misconception.” The misconception, which is depicted as a structure in or of the individual mind, is theorized to be the *cause* of the sentences in which the misconception is expressed—and this independent of the interaction that elicits the sentence, the problematic and perhaps aporetic nature of the relationship between thinking and language. On the other side is environmental (social) determinism, according to which students are said, for example, to do poorly in schools and on tests *because* they come from a low-income family, *because* they are of African American or First Nation origin, or *because* they are male or female, depending on the context. Social constructivism posits some group (society, community, class), which is said to construct knowledge, without providing for theoretical mechanisms that would allow this knowledge to be appropriated into the actions of individuals.

In contrast to deterministic approaches, theories based on dialectical relations emphasize the emergent, indeterminate character of actions, and therefore also of knowing and learning. Depending on their particular cultural-historical origins dialectical theories—e.g., structuration theories in the West, cultural-historical activity theory in the former Soviet Union—provide different sets of concepts. All concepts, however, emphasize the dialectic relationship between the human subject and the object of its conscious attention, which is *sublated* (mediated) in activity, where the verb “to sublate” simultaneously has the sense of “to destroy” and “to preserve” (Hegel, 1977). In other words, subject and object are like two, one-sided expressions of the same phenomenon that transcends and integrates both, including the contradiction they constitute. The phenomenon itself is concrete human praxis, which Marxian psychologists—such as Lev Vygotsky (1989)—attempt to research and understand by conducting *concrete human psychology*. The notion of a dialectical relation is foreign to most Western scholarship and thought; the following analogy is offered to assist readers unfamiliar with dialectics in understanding its nature.

The two faces of a Canadian one-dollar depict Queen Elizabeth II and a loon, respectively. The two sides are clearly different, but in their difference, they are also the same—namely literally “one-sided” expressions of the same one-dollar coin. In purchasing something, however, it does not matter which side is up and recognized; the purchasing value is the same for both customer and salesperson. To express the dialectical relation, the fundamental concept relating subject and object is expressed in the form of *subject|object*; here, the “|” denotes a “not and” opera-
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Diagrammatically, the structure|agency dialectic is represented in Figure i.2. Fundamentally the dialectic expresses that when I study social-psychological phenomena, agency|sensibility (my organs, which allow me to act and my senses) and structure (embodied schema, external resources) mutually constitute and presuppose each other. But they are opposite faces of the same coin—and this in a double sense. First, what I can do with my organs arises from the schemas I embody—built up over the course of my biography—and the resources I find in the world outside of my bodily surface. (This is where radical constructivists get it wrong: without a boundary in the material world, there could not be an “I” that experiences itself as different from the remaining material world, an “I” that can make the difference between self-touching and touching-the-other.) The knowledge exists in the form of bodily schemas, which come in sensorimotor (including articulatory) varieties and, as shown here, are not independent of each other. Practical actions therefore arise indeterminately from the schemas|resources relation (Figure i.2). This relation is dialectic, because schemas and resources are both different, therefore non-identical, and the same, identical, because the schemas mediate my perceptions of the resources.

Second, the schemas|resources dialectic arises in the course of experiences in the world, which is itself the product of my experiences or rather, my agency/sensibility. A frequently cited experiment in support of this dialectical relation is that involving pairs of kittens (Held & Hein, 1963). For a few weeks, one kitten of each pair pulls a cart in which the other is placed. Both sets of kittens therefore have perceptual access to the same material setting, but only the kitten pulling the cart
TOWARD A SINGULAR PLURAL PERSPECTIVE ON SCIENCE LEARNING

actually moves about in it. When the pairs of kittens are tested at the end of the experiment, only the one that has pulled the cart recognizes edges and walls, that is, the structured resources in the setting, and therefore behaves normally as any other kitten would. The one that has been pulled around for all of that time, however, behaves like a blind kitten, bumping into walls and falling over edges; in the worlds of the kittens that have been carried around, the walls and edges do not to exist. As a consequence, any organism perceives the material world because it has developed specific schemas; but it develops these schemas because it perceives the equivalent material structures (i.e., resources) in and of the material world.

When the researchers open up the kitten brains, they find ten times the amount of myelination in the kittens that have moved about compared to those that have been pulled around. The conclusion with respect to the present discussion is that the structures—embodied schema and external resources—both come into being as a product of the kittens’ agency; but, of course, without the structured material world, walls, edges, and the kittens’ material bodies with their specific articulations (length of bones, nature of joints and body parts), the agency would not have been possible in the first place. That is, the senses, which constitute the interface between the world that I experience as lying outside myself and my inside, are “tuned” by my previous experiences so that what I can experience at any one point in time is mediated by the traces that all prior experiences have left in my body. Similarly, what we can do in the world (by means of “organs” [Figure i.2], hands, feet, mouth, body in general) is mediated by what I objectively perceive to be the case, the possibilities for action and the resources available to me.

To reiterate, agency and structure are dialectically related. More so, because structures of the world have arisen from the kittens’ experiences that correspond to their bodily structures, the schemas they have formed are more typical for cats than for human beings or flies. The kittens experience the world as having very different resources for action than newborn children or recently hatched flies. The structure of an organism’s body and the actions and perceptions it mediates (affords and constrains) the schemas it develops (Uexküll, 1928/1972). And finally, because the kittens are not identical to start with, they have different experiences; this leads them to have different structures (schemas and perceived resources) and therefore to individually different worlds. But although each kitten differs from others in the particular schemas it evolves, these schemas are more similar than when each is compared to the schemas that a human being or a fly develops moving about in the same material setting.

These results lead to an aporia (perplexing and possibly unsolvable difficulty): How can I learn, then, which means, build new schemas that are associated with new resources available to me? In this book, I provide answers to this question.

The original agency/structure dialectic as found in the literature has limitations in the sense that it does not make thematic the fact that to perceive anything at all, living beings—flies, cats, and humans—have to be endowed with sensibility. It is sensibility that together with agency affords understanding the evolutionary and cultural-historical nature of the human psyche (Holzkamp, 1983). Sensibility is foundational to intentional life, seeking food, satisfaction of needs, and so forth. It
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is only because of my sensibility that the world can enter and affect me, as an impression on my skin, a sensation of heat or cold, a fleeting image on my retina, or a smell. The nature of structure given by the schema|resource dialectic presupposes the agency|sensibility dialectic, paradigmatically exemplified in the phenomenon of touching (Derrida, 2005), which sublates agency (reaching out) and sensibility (sensing). The intention to touch implies abandoning to being affected by the (re-) action of the touched on the person touching. It is this sensibility that opens my body to experience, allows me to be affected, underlies my openness to experience as such, and therefore the formation of anything like the dialectical relation between the structures of the sociomaterial world and personal schemas. Although I can intend to sense I cannot intend the contents of what my senses will offer to me. There therefore is a fundamental passivity involved in the very (intentional) act of sensing, finding out about the world by allowing it to impress itself upon me. This passivity, or rather, the passivity of passivity is antecedent to all being, is otherwise than being and therefore beyond essence (Levinas, 1978a/1998).

LIFЕWORLD

The world characteristic for species and individuals is denoted variously depending on discipline; pertaining to human beings it generally is referred to by the term lifeworld. My lifeworld is the world given to me in my experience in the way it provides me with resources for actions. I act toward the things and events that perceive. Thus, if I perceive ghosts, then I act in a world populated with ghosts. To understand my actions—why and how I do what I do—others have to take the ghosts into account. If they do not do so, then my actions no longer are logically connected, irrational, and illogical. Similarly with learners: when I, researcher, observe them, I need to understand their lifeworld to understand what they perceive, what they do, how they do it, and why they do it. Alternatively, I have no recourse other than saying that their actions are wrong—where I have to assume that they act toward the structures available to me—or, worse, that the actions are unintelligible and incomprehensible. But such an approach is untenable because actions are inherently social phenomena, for each individual “sees the other do the same as it does; each does itself what it demands of the other, and therefore also does what it does only in so far as the other does the same” (Hegel, 1977, p. 112). The frame for understanding actions in this way is the societally mediated activity in and for which they are produced—more on this in the subsequent section.

My lifeworld is a dwelling that welcomes me; but it is a dwelling of my making. All intentionality therefore also is hospitality, where I, the host, offer welcome to the other, material entity or person (Derrida, 1999). But I am host only because I already have been welcome in my own dwelling, which is not completely mine. The lifeworld predates my (conscious) being in the world; it is itself associated with a third, the society into which I have been born. Therefore, even the most phenomenological inquiry leads me to articulate structures of knowing and learning that are not inherently mine but always already possibilities (acting, knowing,
learning) that also consist for others. This, too, derives from the singular plural being of the world.

The fact that a specific material setting constitutes different lifeworlds—constitutes a different dwelling (disposition) for different individuals—is immediately evident when considering the following example. My kitchen provides me with specific possibilities for action; I act in specific ways because of the opportunities and constraints that the kitchen provides me with. Any other person inherently has a different disposition and therefore does not perceive the same possibilities and exhibits different actions to some outside observer. Yet both sets of actions also share similarities, which arise out of the material constraints of the kitchen, limiting, for example, what can be cooked and where. When I visit others and cook in their kitchen, I am confronted with a different set of possibilities, opportunities and constraints: the kitchen is not only materially different, having a different layout, different stoves, and knives of different quality, but also I experience it differently. That is, the Michael-in-another-kitchen corresponds to a different person—lifeworld ensemble. And yet there are similarities between other kitchens and my own, in layout, collocation of knives, forks, and spoons in a common cutlery tray, placement of particular foods in the fridge (milk, vegetables), and so on. My previous involvement in and with such places as kitchens has left (i.e., inscribed) in me traces that mediate the possibilities and constraints I perceive and therefore the actions I produce in the pursuit of the goals I have framed.

The upshot of these considerations is that to understand what I do, a researcher needs to know how the world looks like to me, what my lifeworld is at the time, and what the opportunities and resources are that I perceive. It does not help a bit to consider a physicist’s description of the kitchen (using, e.g., Cartesian coordinates) and the materials that fill it in the attempt to understand the actions of a person, why and how she does something. This is among the core concern of this book: understanding the world through the eyes of learners, the possibilities and constraints they objectively experience in particular settings, and how any knowing and learning unfolds from that.

The problem of many theories of knowing and learning is their presupposition (i.e., pre-sup-position) that the world is entirely represented in the mind. Human beings, however, do not have full and therefore monolithic internal mental models of the world. As implied in Figure i.2, I am bound up with and organically (senses, organs) connected to my lifeworld. I am an integral and constitutive part of my lifeworld; my lifeworld and I always go together. Because the material world is structured, there are opportunities and constraints for my acting and sensing; and these opportunities and constraints, I find in the world. I do not have to carry them around in my mind. Human beings tend to minimize the thinking tasks and the internal representation of the world; I am not and do not have to be a robot that keeps track of things in terms of physical coordinates and extensions but I take the world as it is. Whatever I perceive as entity, I can use as a resource in my actions. Rather than keeping a full model of some scene that I am looking at in its entirety, I can leave much of the information in the world until the moment that some information is required in my task. Thus, for example, I do not need to memorize all
or any of the features and tools of my word processor because I know I have every-
thing available and can find it when needed as I am working along in producing
this manuscript. This is not to deny that there are undoubtedly some things in my
brain that can be attributed to human reasoning and decision-making. But relevant
to my behavior are those structures in my material environment that I experience as
objectively given and that I use in (non-) conscious ways. (Non-conscious means
that they can become or be made conscious.)

In this sense, the social world, too, has to be understood as objectively given to
me in my experience. It, too, is needed in phenomenal accounts of my lifeworld,
because it is toward it that I orient and act. If I experience another person as power-
ful then I will act in ways—e.g., deferentially—that produces and reproduces a
power differential.

Perhaps the most obvious and most overlooked (with the exception of the phe-
nomenological literature) aspect of human knowing is that it is embodied: I am
continuously coupled with my material and social environments (Figure i.2) be-
cause I am (material, social) body among (material, social) bodies. In fact, it is
difficult to draw the boundary between the material setting and myself. From the
perspective of an oxygen molecule, does my body start at the lips, in the larynx,
lungs, or bronchi? Or does it start when the molecules come to be attached to a
blood cell? Does the boundary between my finger and the thing I touch belong to
the inside or outside of my body? I develop some of these ideas with respect to
knowing and learning in chapter 5, which deals with the relationship of parts and
wholes, the boundaries that separate them, and how the maps so prepared consti-
tute specific lenses.

Embodiment and material coupling allow humans to use the material world,
including their own bodies, as a tool that mediates the organization and manipula-
tion of knowledge (Nancy, 1992). Through my body, the multifarious ways of
coupling with my lifeworld are brought about and integrated into mutually consti-
tutive (e.g., motor and perceptual components) and supportive (e.g., auditory and
visual) relations. This coupling decreases the demands on any cognitive effort I
have to spend to cope with the demands of navigating the world. Recent work in
robotics shows how systems that capitalize in the way humans do on their situated
nature develop much more robust behaviors all the while being computationally
less complex because certain constraints are already built into real worlds for
agents to use—such constraints include forces such as gravity and friction and in-
teractions with others from the same and other species. Thus again, because know-
ning is embodied, the very existence of the body integrates sensibility and agency,
which decrease what I have to process in thinking and reflecting.

Viewing knowing and learning in a dynamical way, in terms of being connected
to the places (i.e., positions) I inhabit comes with advantages. Dynamical systems
theories converge with phenomenological insights about the central role of the
body and with the body, the central role time and temporality in our knowing and
learning—these issues are taken up in chapter 9. Rather than understanding know-
ing as occurring over time, a dynamical perspective allows me to view knowing as
occurring in time and therefore as an entirely temporal phenomenon. Details of
TIMING

Timing are essential aspects of knowing rather than incidental details; knowing is not a sequential and cyclic process but a process of continuous coevolution. Doing therefore simultaneously is knowing and learning; in doing, I exhibit knowing and because agency is connected dialectically with sensibility, doing implies sensing and learning. Subtlety and complexity of human knowing and learning are found not at some specified time in elaborate static structure, but rather in time, in the flux of change itself (van Gelder, 1998).

SINGULAR PLURAL NATURE OF ACTION

In this book, I articulate and elaborate a perspective of learning through the eyes of the learner, that is, a first-person perspective. Such a perspective, sometimes and often falsely denoted by the adjective “phenomenological,” frequently is taken as a reduction of knowing and learning to the individual subject. That is, knowing and learning phenomena are theorized beginning with the individual subject as the unit of analysis. A typical aporia then arises: “How can intersubjectivity arise when all communicative activity already presupposes intersubjectivity?” Some respond to this aporia by suggesting built-in mechanisms, such as a genetically wired-in basic grammar that allows humans to generate language. The aporia is even more poignant when theories begin with mind independent of bodily existence in the world, because in this case an explanation is needed for how knowledge, which is a matter of mind (consciousness), relates to anything material at all. In the artificial intelligence and cognitive science community, this aporia is referred to as the “grounding problem.” The disconnect between ideas, on the one hand, and the “real” material world, on the other, has been a long-standing problem in philosophy, ever since ancient Greek philosophers first articulated it.

The reverse aporia arises when I begin to theorize knowing and learning from a social perspective (e.g., social constructivism). Typical theoretical terms in related discourses are reproduction, inculcation, appropriation, enculturation, and apprenticeship. The collective entity (i.e., culture, society, group) is thought of as a box into which new individuals (i.e., children, students) enter; this box is said to shape the newcomers until they are acceptable and accepted core members. The collective entity is (inappropriately) presupposed to antedate the individual being. Formulated in this way, learning is a deterministic process, whereby the individual is a dope, who does what he or she is determined to do.

Neither approach is very productive; both only lead into theoretical cul-de-sacs. To understand learning through the eyes of the learner, a simultaneous account is needed of how my actions always are actions that are also recognized by others as intelligible actions, that is, actions that they could have produced. Every sentence uttered presupposes its own intelligibility because otherwise it would make no sense uttering it. At the same time everything I do, even without someone else present, is not a completely singular act. I am singular plural, because what I do and who I am are possibilities that immediately (both instantly and without mediation) exist for and are intelligible by others. What I say and do is always and already intelligible not only to me but also to others because I am held accountable for my
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acts. I do what I do for reasons that are always reasons I can articulate and explain to others; consequently, these actions and their reasons are intelligible to others and, therefore, inherently not just mine but already reasons and actions of the other. They are reasons and actions for the other, of the other, and reasons and actions that therefore return to me from the other so that I can deploy them in turn.

Each act, whether it is a perceptive, discursive, or manipulative act, always is both singular and not singular, individually produced but also reproducing a collective (cultural) possibility. In any one actions, one therefore can identify cultural possibilities; in my singular experience, I can always identify ways of experiencing that transcend the singularity of my own acts. The phenomenological method employed throughout this book is directed at this possibility of transcending the individual toward the culture; and any effort of doing so is itself already grounded in its intelligibility, and therefore constitutes a cultural possibility.

OVERVIEW

This book is divided into four parts, each of which deals with what I have come to consider as a major dimension of learning that past research and teaching praxis in the field of science education have not addressed. In Part I, I present some of the aporias (unsolved and unsolvable problems) of learning science through hands-on investigations and demonstrations. In this part, I revisit some data sources that I assembled in a study conducted in an Australian twelfth-grade physics classroom. Having redeveloped an interest in phenomenological issues of knowing and learning, my personal interests during the study were concerned with better understanding the events through the eyes of the learners. At the time, I wanted to understand why students were saying what they did, their reasons for acting, and what they perceived, which, as I thought, would mediate what they said. I assumed that students are not voluntarily and mischievously inconsistent or irrational but rather that they acted in ways that made sense from their position. My program was this: To do justice to student actions that others—teachers, researchers—might characterize as irrational or as defective, I needed to enter and understand the lifeworld of these students, that is, I needed to see the world in their ways. In this first part of the book, learning from perceptual experience and the nature of perceptual experience itself arises as a fundamental aporia: To know what the teacher wants me-learner to perceive in an experiment or a demonstration, I need to know the phenomena that I am asked to look for; but to know the phenomena I am asked to look for, I need to be able to perceive them. This aporia is taken up and at the center of the second part of this book.

In part II, I present three chapters dealing with the aporia of perception. The materials for this and the subsequent parts III and IV have been assembled during a three-month stay as a fellow in the cognitive neurosciences section of the Hanse Institute for Advanced Study. I used this stay, among others, to do an extensive and extended analysis of perceptual experience and how I, being singular plural, come to see in and through experience. In addition to closely watching a set of videotapes featuring tenth-grade students in the process of learning about static electric-
ity through hands-on explorations in small groups, I equally closely attended to and recorded my own perceptual experiences. These experiences came about while I attempted to understand what was happening in the tapes, while I conducted investigations using the same materials that students had available while taking the class, and while I cycled to the university or while I went on a bicycle trip designed to provoke perception in an unfamiliar environment. In this second section, I therefore show how I (we, students) come to perceive, how my (our, students’) lifeworld unfolds and becomes increasingly articulated, and how I (we, students) develop maps for perceiving and understanding the world, maps that actually constitute disciplinary lenses.

Part III of this book is devoted to the relationship of world, lifeworld, and language. The latter has received very special treatment by science educators, as if it had an ontological status apart, that is, as if it was different from other things that humans use to communicate, such as hand gestures, pointing, head nods, and things in the setting people are attuned to. Rather than beginning to think about communication in terms of language, subordinating the former to the latter, I begin with communication and subordinate patterned sounds to communication generally. I show how sounds are part of taking up position and orienting in the world and how they exist side-by-side with other communicative forms. The special status of language derives from the fact that it often better serves to talk reflexively about bygone situations and communicative exchanges than other communicative forms do. Taking this position also gives me a better handle on how discourse emerges from hands-on investigations and how language is related to other communicative forms in the process of the evolution of understanding and theory, especially the split between the material body of the signifier and the sense that is signified. Finally, I am concerned in this part III with the reverse relationship between language and manipulation when I investigate how instructions are followed and implemented, or rather, how actions are related to instructions in such a way that I can say that the latter have been followed.

In part IV, I deal with time and temporality in learning through engagement with material things, including the experience of flow and the temporal constitution of objects, tools, and knowledge. In chapter 9, I show how time and temporality are central aspects of the experience of knowing and learning and result from experiences in and of the world. In the subsequent chapter, I describe an instance of learning where I, an individual who has previously received a M.Sc. degree in physics, learn some new things about static electricity and how to understand the specific phenomenon of charging a metallic object by induction. In the final chapter of part IV, I show how a tool comes to be known theoretically not through its use, but in a variety of situations that make its aspect the object of intentional activity, including moments of breakdown or moments in which the unanticipated nature of an observation becomes salient.

Throughout this book, I draw on materials that come from either a twelfth-grade (chapters 1 and 2) or a tenth-grade (chapters 4–7, 9, 11) physics classroom. However, the investigations in which students engage in are not esoteric. Rather, these are so simple that they can be conducted at home; and I have found descriptions of
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them in elementary school curricula. Thus, in the twelfth-grade class, students investigate, for example, objects rolling down an inclined plane; or the students observe someone sitting on a rotating stool spinning a bicycle wheel. In the tenth-grade classroom, students investigate the electrostatic charging of objects. Charging objects can be done at home using different types of materials, woolen cloth, transparency sheets, combs, and so on; tests for the presence of charges can be conducted using bits of Styrofoam, paper snippets, or simple electrosopes made from the silver paper found in cigarette boxes or chocolate bars—paper part removed. Throughout the book I also use drawings to make available what students and teachers have seen or might have seen, thereby providing readers with a way of seeing for themselves.

METHODOLOGICAL REFLECTION

This book is the result of my attempt to provide a learner’s perspective on learning in science. Whereas it is easy to talk and write about what one perceives and to provide reasons for one’s own actions, it is more difficult to note what someone else perceives and to know why they do what they do, unless they explicitly articulate and thereby make available to others their reasons in the course of action. To deal with the inevitable constraints in writing about learning from a learner’s perspective all the while writing about the learning of others, I draw in this book on my own perceptual experiences and learning as well as on my observation of others. Here, I am not interested in my experience per se, but in what I can learn about learning more generally, that is, about aspects of learning pertinent to the plural in being singular plural. To reiterate, I am not interested in my perspective or position, but in the structures that make this perspective possible in the first place and how another perspective could have easily replaced it. I am interested in articulating why there are different forms of experience rather than merely describing them.

Although my perspective is not at issue, I nevertheless use the first person pronouns “I” and “me” and the reflexive pronoun “myself” in places where other texts might use “our,” “you,” “one,” and so on. I chose this form because of the general intent to present a first person perspective on learning; I could have equally used the first-person plural forms “we,” “us,” and “ourselves.” I am not interested in portraying a specific person’s position but rather emphasize the fact that the perceptions of all human beings are their own all the while recognizing that each perceptual act and the verbal articulation of its contents is a possibility that also exists for other human beings. That is, each individual action is singular plural, both inescapably individual and radically sociocultural and cultural historical.

With respect to students who learn science, I cannot make the assumption that what I am seeing while observing the tapes—for example, that a lamp glows or a pointer moves (Figure i.1)—is exactly the same as that what they have observed. Perceptual experience always is singular. In fact, I show in chapter 1 that even within the student body, the same material event is perceived in very different ways. It is difficult to say based on watching a lesson whether or not some material that students are currently using “really has been charged” and, if so, a student
“really” perceives it as such unless he or she articulates the perception. The video-tape cannot provide evidence for that. The video only shows that a person has rubbed one material against another. Whether it is in fact charged can not be established until an electroscope pointer begins to move, a lamp when brought close begins to glow, another piece of material is attracted, and so on. But when none of this happens, I still cannot be certain that the material was not charged. That is, to be able to make a statement about what is the case in any one situation, I (researcher) have to look for evidence: to say something about what a student perceives I have to provide evidence that this is the case. For example, when a student says in surprise, “Oh, this thing is not connected” after having attempted to use some tool for some time without success, I have supportive evidence for a claim about her not having seen the lacking connection—which may in fact be the way the tool is built so that two wires do not connect. Surprise, statements about noticing something for the first time, and discovering (presumed) causes of material breakdowns all are events that hint at what is currently salient in someone’s perception.

Throughout this book I use pseudonyms, even though it is nearly impossible to track down the original schools and classrooms where the data sources have been constructed initially. To make it easier to distinguish students and teachers, the first names of the latter always begin with the letter “T,” whereas the first names of the former begin with letters other than “T.” Throughout the book, I use drawings rather than photographs because they allow me to reduce the amount of unnecessary, gratuitous detail, thereby making it easier for readers to perceive what I intend them to perceive.
PART I

APORIAS OF LEARNING SCIENCE
Aporias are perplexing difficulties or problems that may not have any solution. Thus, the inner contradictions of dialectical notions and the corresponding resistance in the material phenomena they denote constitute aporias: they are irremediable and unsolvable. Learners are exposed to a number of fundamental aporias that make us wonder how anyone can learn any science. The most fundamental aporias include: (a) How can I learn science if it requires my prior experience, which, in the final analysis always is everyday, mundane, and non-scientific? (b) If observation is theory-driven, how can I, who always already comes with a mundane understanding of the world, a disposition, make observations that support a fundamentally different pre-scientific ontology (collection of worldly things) and non-scientific theory? How can I know that what I see is what I am supposed to see? How can I know that what I do in laboratory task is what I am supposed to do?

The answers to all of these questions require me to deal with the fact that teaching science presupposes the perceptual experiences and explanations that they are supposed to teach. For me, a learner of science, the fundamental aporia therefore exists in the fact that I have to intentionally aim at learning something that I do not know what it is. This is an aporia, as an intention is always object-directed. Thus, if there is no object, for example, because it is unknown, I cannot have an intention directed toward it. It is as if I had to be able to provide a roadmap to get to an unknown place in an unknown country prior to having roamed it for some time to become familiar with it. Christopher Columbus could not intentionally go to the Americas, as he did not know about the Americas. Asking students to learn something they do not yet know is like asking Columbus to discover Cuba without being able to give him descriptions of what it may be like to face this island. And yet, in my search for what it is I am to learn, the things I am in the dark about, I always already bring some light, my existing practical understanding of how the world works. Columbus had some hunch about the shape of the earth, which would get him to India if only he kept on sailing westward. It is with this light, or, as presented in chapter 5, with a particular lens that I begin all learning in a chicken-and-egg situation: to overcome my everyday mundane discourse and appropriate a new, more scientific discourse, I have to rely on the former. To change my disposition, I have to change my position (dis-position), which always is a change from the position (dis-position) I am currently in: to “overcome” my everyday, mundane way of seeing the world to develop a scientific perspective, I nevertheless have to rely on and ground new perceptions in, my current non-scientific ways of seeing.

In this part I, I revisit and reinterpret my observations made during a study of physics learning in an Australian classroom, taught by an experienced, highly
knowledgeable, very willing physics teacher whom I refer to as Toby Mory. In the first chapter, I focus on possible reasons that might mediate what students actually perceive and why they do not agree among themselves and with their teacher about what it is that can be seen in a demonstration. My analysis reveals six dimensions that may have prevented students from perceiving a demonstration in the way Toby had intended it and therefore what they could learn from a demonstration. These dimensions include (a) students theoretical framework that did not yet separate signals—the phenomena—from noise, (b) interactions with discourses learned in other contexts of the physics course, (c) interactions with traces of other demonstrations and images that had some surface resemblance, (d) students’ difficulties in piecing together coherent representational frameworks from the information given, (e) low salience of demonstrations on tests, and (f) lack of opportunities for students to test their descriptions and explanations.

In chapter 2, I provide a fine-grained description of students’ discursive and material actions in the same traditional senior physics class. From a first-person perspective, I focus on the processes by means of which students bring order to their observations and material practices. In the process of their ordering work, the phenomena students articulate in the laboratory arise from an intertwining of embodied material and discursive practices, the possibilities and constraints of the material world, and their relations with other people. They evaluate the adequacy of any action by means of an interpretation of its outcomes and not by means of an assessment of the actions themselves, which leads them to a contradictory situation: To know that they have seen what the teacher intended them to see, they need to know that what they have done is what they are supposed to do; but to know that what they are doing, students need to know that what they are seeing is exactly what they are supposed to see.
CHAPTER 1

APORIAS OF PERCEPTION IN SCIENCE

The focus in this book is on laboratory investigations in which students learn and learn about science in and through their own investigations. However, laboratory tasks require students not only to observe but also to prepare the phenomena that are of interest to scientists and that in fact constitute the world that scientific formula, concepts, and theories really describe. There therefore is the potential that students do not see a phenomenon because they have prepared something very different. Thus, to get a handle on perception first, I focus in this chapter on teacher-presented demonstrations, in which those phenomena are present that the teacher uses as basis for his or her explanations of concepts and theories.

In chapter 2, I describe high school physics students who do not generate the phenomena that the teacher wants them to generate and therefore they do not see what he wants them to see. I take a quick look ahead to properly contextualize the concerns in this first chapter. In chapter 2, my descriptions highlight that students are coping with instructions that pose them with an aporia, an unsolvable problem:

1. to know whether they do what they are supposed to do, they need to know what they see is what they are supposed to see; but
2. to know that what they see is what they are supposed to see, they need to know that what they have done is what they were supposed to do.

This aporia constitutes a serious situation for any teacher who wants students to learn legitimized and legitimizing science knowledge through discovery and inductive reasoning. Some science teachers perhaps want to suggest that the time in the laboratory might be better spent looking at demonstrations, which the teacher can set up such that the scientifically relevant phenomena rather than any other can be seen. This would then be the equivalent of what Michael Faraday had done when he sent equipment to his scientific peers so that they would reproduce his experiment and therefore arrive at his observation descriptions and observation categoricals rather than their own. One may ask, however, whether producing demonstrations will solve another aporia: If I need to know a phenomenon to perceive it, then how can students perceive a demonstration scientifically given that they come with their own everyday, mundane ways of seeing things? They come with dispositions that do not overlap with scientific dispositions required to perceive the phenomena scientifically. What will they perceive given a particular demonstration? These are the questions I track in the present chapter. But let me begin by taking a look at the classroom episodes from an Australian twelfth-grade physics course; here, the teacher Toby Mory, who loved to design demonstrations, frequently used them not
only because he could illustrate scientific concepts but also because he thought these demonstrations might motivate students.

A DEMONSTRATION OF ROTATIONAL MOMENTUM

Toby picks up a bicycle wheel and sits down on his rotating stool, which is hidden from view for all but the students in the first row (Figure 1.1). He invites students to observe, “So alright now there are a few other ideas we can put together with this, I got the bicycle wheel, some kind child donated it. Now just watch very carefully, at least you can see the part you need to see, that is the top of my body and the wheel. Right, watch carefully.” He rapidly spins the wheel with its axis vertical, that is, parallel to the axis of the turning stool. This is associated with an almost unnoticeable opposite spin in his body. Toby comments, “This chair isn’t very good I’ll try that again.” This time, the chair makes about an eighth of a turn. “Did you just see it? Look again,” he urges, “look at my body mainly. What was my angular momentum just now? Zero, I’m isolated sitting in this awkward looking position. When I spin it what do you notice?” Norm calls out, “Opposite to the wheel.” “Yes I’m going the opposite way to the wheel. When we are looking at these vectors, to start with L was zero wasn’t it? That’s my angular momentum. It’s made up of two things: My angular momentum and the wheel’s both zero to kick off with.”

Toby walks to the chalkboard and writes

\[ L = 0 = L_{\text{me}} + L_{\text{wheel}} \quad (1) \]

Figure 1.1. While sitting on the rotating chair, the teacher spins the bicycle wheel. When the axis of the wheel is parallel to that of the chair, the latter rotates in the opposite direction of the chair. When the axis of the wheel is perpendicular to that of the chair, no movement should be observed.
where he uses the convention of underlining the letters that denote vector quantities (i.e., variables that have magnitude and direction and therefore can also be represented by arrows). He continues, “The angular momentum is the vector and has direction, this is how we measure the direction of angular momentum. You see when I spin that, when it spins, if I put my fingers in the direction of the spin my thumb comes out the axle.” He curls the fingers of his right hand in the direction of the turning wheel, while sticking out his thumb (as in Figure 1.2). “So that was taken as a vector representing angular momentum. That vector,” he says while moving his hand a bit thereby attracting attention to the thumb sticking out, “it’s a radial vector. If I spin it that way that’s the vector; if I spin it reverse, my fingers that way, the vector would be going down.” He repeats the curling of the hand with the thumb pointing along the bicycle wheel’s axis every time he talks about direction and vector. “It’s not a real vector like linear ones. It’s called a radial vector or an axial vector. It’s the direction of the axis using a right-hand grip rule. All right? Now when I’m down here and spin it that way, it now has a value of \( L \) vector pointing upwards of so much magnitude. How long that arrow is, depends upon—I’d have to do an \( I\text{-}\omega\text{-squared} \) for the wheel ((angular momentum: \( L = I\omega \); angular kinetic energy: \( E_{\text{kin}} = \frac{1}{2} I\omega^2 \)). My body went the other way, didn’t it? How did I spin the wheel? The wheel was going that way, my body rotated the other way, my body had a vector thus, so it was a positive vector, a positive angular momentum, so my body would be that.” He gestures with his thumb upwards, and by gesturing drawing attention to it. He continues, “So this takes on positive; my body took on negative [angular momentum]. When I stop it ((he stops the wheel)), the reverse happens doesn’t it?”

At this point, Toby sits on the chair (Figure 1.1). “So alright, have a look at this one. I’m going to spin it this way and nothing will happen because there’s no way I’m going to let my body rotate.” He spins the wheel with the axis at a right angle to the axis of the stool. “Hang on, I’ve just got to turn that up,” and turns the wheel’s axis 90 degrees. The stool rotates about one quarter turn. “Did you see that? I’m going to stop it.” He stops the wheel, and the stool returns into its original position. He explains, “See what happened to me? This was going in that way,
rotating that way, vector upwards.” Again, he curls his hand in the direction of the wheel’s motion while sticking out his thumb. “When I stopped it my body took it on and my body took on that angular momentum see.”

After repeating the demonstration twice, he is about to move to the next demonstration, when Andy calls out a question, “When you turn this ((points to the wheel)) over will that do it in the opposite direction which will also help you stop? When you turn that over one-eighty degrees?” Toby responds, “That’s what I want you to think about; why, when I turn it [wheel] over did I reverse. Now I should keep spinning if it wasn’t for the darn friction in this chair.” Andy is not satisfied, “But now, the chair’s, the wheel is pulling a force which is stopping you if you turn it over one-eighty degrees.” Toby replies, “I’m not even mentioning forces here, I’m an isolated system, by turning it over, at all times all I know is big L for this whole system is zero.” Andy insists, “Just turn it ninety degrees.” Andy goes on further to ask if Toby has the same qualities as the bicycle wheel, would he spin at the same speed. Toby says, “What’s that? Comparably but the other way, yes” and moves on to demonstrate another example of the conservation of angular momentum.

This is a typical example for the many demonstrations Toby presents to his students during this and other lessons on angular momentum. It is typical in that he is doing most of the talking most of the time. He interacts little with students, especially in the way one can see in this episode where a student insists on pursuing some issue. In fact during my six-week stay in this classroom, there only are two such interactions, the second one involving Christina as described in chapter 2. At the same time, all observers in the classroom agree that the numerous demonstrations are skillfully performed and a rich source of applications of angular momentum. The posttest results, which included interviews with ten students, then come as a little surprise: in a demonstration of the same phenomenon using a low friction turntable rather than a stool, four students show the direction of the vector representing angular momentum as shown by the teacher (Figure 1.2); and of these, three also know how to indicate angular velocity by means of an arrow (vector). These are the only students who draw on the conservation of angular momentum as a resource to explain why there is little or no movement when the axes of the wheel and turntable are (nearly) perpendicular, but a considerable rotation of the turntable in a direction opposite to that of the wheel when the axes are parallel.

The videotapes of this classroom exhibit similar issues in the context of other demonstrations. Toby likes to develop demonstrations, spends much time in developing and building demonstrations that he uses to illustrate the standard principles students are to learn. In some sense, he earnestly tries to provide his students with a rich and varied experience. But all data sources collected in the classroom provide evidence for the claim that most students in this classroom fail to understand many of his demonstrations and the physics lessons to be learned in them. Although the demonstrations are technically well prepared, and although Toby talks about the major concepts involved, students learn little from these demonstrations. This raises the question, “Why do these students learn so little from Toby’s demonstra-
In this chapter, I articulate some of the features of the lessons that may mediate students’ failure to learn the intended lessons. My interest here is not to blame the teacher but to highlight those features of the most well intended lessons that interfere with student learning. I feature those aspects of demonstrations that constitute a fundamental aporia for learning in this mode.

DEMONSTRATIONS AND OBSERVATIONS

Science teachers often employ demonstrations to exhibit scientific principles in action. However, there may be some problems with this practice. It is widely accepted that all observation is interpretation. Because interpretation arises from the interplay of existing understandings (prior experience) and the world, what I (in being singular plural) observe depends on what I already know, on my present disposition. It is unlikely therefore that students who do not yet know the relevant scientific principles will see just what the demonstration is to show, for the very principles that are to be exhibited are prerequisite to seeing the intended phenomenon. That is, students perceive science demonstrations differently from teachers and scientists, a fact that mediates what they can perceive and how they can articulate it in observational language. As I show in chapter 3, not only students but also experienced scientists reveal a relevant world in and through their individual interactions rather than comprehending this world in its entirety when they first lay their eyes or hands onto it. That is, even in the demonstrations learners are faced with the fundamental aporia that to perceive what they are supposed to perceive they need to know and understand the phenomena; but they are presented with these demonstrations because they are supposed to learn to perceive and explicate them. The upshot of this is: more than simple exposure to some event through a demonstration is required if students are to learn.

Most research regarding learning assumes the existence of an inherently structured world with clearly identifiable phenomena. Phenomenological and pragmatist philosophers consider this assumption problematic and even untenable. It is easy to show that perceiving the world around me with specific objects and properties is not a self-evident process—I explore this in subsequent chapters—and, as seen in the next chapter, students structure the world differently from their teachers and the community they represent. To understand students’ talk and manipulations in science classrooms, it is therefore helpful to model the presumed ontology (i.e., ensemble of objects and events perceived) of the lived world as ambiguous and undetermined before the act of interpretation. Through the interpretation of perceptual experience, objects become the things I know of together with their specific attributes. Specific interpretations arise from the interaction of the horizons (presuppositions, dispositions) I bring to a situation and the material world. That is, my interpretive horizon has formed in previous experience and is embodied in the practical competence of seeing something as something. Recent neurophysiological and neuropsychological evidence supports this: all signals—e.g., from the eye to the brain—are filtered, modulated, and shaped by signals from the brain to the eye. What hits my retina is not what is available to my consciousness—but this issue has to await a description of novel perceptual experiences as I articulate these
has to await a description of novel perceptual experiences as I articulate these in chapter 3.

There are other descriptions of knowing and learning that question traditional conceptions of demonstrations. Etymologically, the word *demonstration* derives from the Latin *monstrare*, to show, point out; and *de*- is a reinforcing device. To be able to recognize that which is strongly made explicit and pointed out, I already must be able to perceive it. But *perceiving it* requires that I master the theoretical framework, that is, the observation sentences and observation categoricals that the demonstration is intended to facilitate my learning of them. That is, a demonstration works for those who already know; it is an inherent aporia for the learner familiar neither with phenomenon nor with the theoretical frame that supports it.

A new relationship between descriptive and explanatory language and visibility of phenomena has been suggested in recent work in the history and philosophy of science (e.g., Pickering, 1995). Accordingly, discourses—or rather and more poignantly, observation categoricals and the theories issuing from them—and the world I perceive are mutually constitutive: they presuppose each other. They are and do so, but not in any simple fashion; rather, their relation is dialectical and indeterminate. Material practices (manipulating objects, artifacts, tools) and discursive practices (observation sentences, observation categoricals, theoretical explanations) coevolve and reify each other. There is historical evidence that initially, Galileo Galilei could not see motion on the inclined plane as I see it today. His understanding of velocity and the linear relationship between instantaneous velocity and time came about only after he changed his notion of *velocita* (average velocity) to the present day notion of instantaneous velocity. In his days, two accepted pieces of knowledge mediated his seeing and understanding. First, ratios could only exist between like things (four stones and two stones), not of two unequal things (e.g., distance and time) as is required for the modern notion of velocity. He therefore could not conceive of the ratio of distance traveled and the time it took to cover this distance. Second, he could not conceive of an instantaneous velocity, the distance an object covers in the course of a time interval that approaches zero seconds in the limit. Without a theoretical discourse about velocity, there is no phenomenon; and without the phenomenon, a discourse that describes and explains it is of little use.

To understand this relation between the things perceived and my descriptions of them, the philosopher Martin Heidegger (1977/1996) uses the notion of *articulation*, both in the senses of *utterance* and *joint*. I articulate, that is, tell the world into wholes and parts exactly where it has its joints, *articulations*. Words and language therefore have no other use than helping human beings to point out what is and can be articulated, perceptually. That is, I can articulate something as something only when I perceive it as different from everything else. In other words, observation sentences require corresponding things perceived; entities and processes in the world and the sentences that describe them presuppose each other in as far as they are relevant to my actions. By analogy, I can also talk about (articulate) things that are not available perceptually but nevertheless constitute jointed wholes and parts.
As I conducted research in this Australian science classroom, I formulated an assertion stating that students learn very little from the many demonstrations performed by Toby. To test this assertion, I constructed a posttest task that was very similar to one of the demonstrations differing only in the object that permitted the person to spin: Toby sat on a rotating stool during the lesson (Figure 1.1) whereas my fellow researcher doing the demonstration during the posttest stood on a rotating table. The drawings accompanying the test questions have high epistemic fidelity: the naturalistic drawings of objects, direction of motion, verbal descriptions of motion and objects, and perspectives are as they can be perceived them from the students' seats (positions).

A standard explanation of the situation in Figure 1.1 runs as follows (Figure 1.3). The rotating chair or table (and person sitting/standing on it) with an axis in the vertical direction has an angular momentum of zero \( \mathbf{L} = 0 \). As long as the bicycle wheel’s axis of rotation, and with it its angular momentum \( \mathbf{L}_2 \) is perpendicular to that of the rotating table with the person \( \mathbf{L}_1 \), it remains at rest because the angular momentum of the bicycle wheel does not carry over (Figure 1.3a). If the bicycle wheel is turned so that its axle has a component parallel to that of the turntable, the latter begins to rotate in the opposite direction (Figure 1.3b). Taken together, the momentums of the bicycle wheel and that of the rotating chair or table cancel out so that total angular momentum is conserved \( \mathbf{L} = \mathbf{L}_1 + \mathbf{L}_2 \), that is, has a value of zero.

On the posttest, only three students provide the answer that Toby Mory expected. In two of these instances, the direction is inconsistent with that of angular velocity, although the students invoke the relationship according to which angular velocity and angular momentum have to point in the same direction. Eight students

![Figure 1.3](image_url)

*Figure 1.3. The standard explanation of the experiment depicted in Figure 1.1 is based on the concept of conservation of momentum. The rotational momentum in the direction of the rotating chair or table initially is zero. a. As long as the axle of the spinning wheel is perpendicular to that of the chair or table, nothing is observed. b. When the two axles are parallel, the chair or table moves in the direction opposite to the wheel so that the momentums of the two taken together cancel out.*
use arrows either parallel to the axes, or curved and parallel to the trajectory of the rims of wheel and chair or table, as I have drawn them in Figure 1.3. Twelve students do not respond at all or indicate, “don’t know.” Even Sean, one of the highest achieving students in this course, does not infer the direction of the angular momentum vector:

Angular velocity. It’s like the momentum. Not sure about the direction of it. Mr. Mory hasn’t told us yet or I probably didn’t think or couldn’t remember it. I wasn’t sure what the actual direction was that the arrow represented so. . Well I obviously had an idea on vectors, and they have magnitude and direction. I couldn’t recall the direction, so I just gave the magnitude value.

When asked to explain why the person on the low friction table spins when the wheel is turned as indicated, four students provide explanations that the teacher accepted as correct. These explanations invoke the law of conservation of angular momentum. Three students provide explanations in which the direction of the table’s and the wheel’s axis is the central feature. Seven students explain the situation by drawing on forces and torques or action–reaction systems. For example, Allan suggests:

It is a closed system. The force of the wheel caused his body to turn. Every action has an equal and opposite reaction. Therefore his body turned in the opposite direction to the spinning wheel.

Like many of his peers, Jon brings his prior understanding from Newtonian mechanics into play to interpret what he has seen:

Instead of talking of the momentum I was talking about the forces and direction and so I think I was talking about the forces activating the wheel, like friction and stuff like that instead of actually momentum.

Nine students suggest that the total angular momentum changes (although the system is to be considered closed from a physics perspective). Ten students provide no explanation at all.

In this situation, Toby, a well-intentioned teacher has presented a classical demonstration couched in the typical discourse about the topic. From his point of view (position, dis-position, and disposition), he has provided all the requisite knowledge pieces to “construct” an understanding of the phenomenon. Students observe and, despite all the explaining, gesturing, and writing on the chalkboard Toby performs, exhibit little if any understanding of the theory that the demonstration is to exhibit. Readers can already imagine that there are a number of mediating elements that make it difficult for students to learn. For example, if they perceive no movement in a demonstration but the teacher’s explanation is intended to explain why an object moves, then students have difficulties integrating the contradictions. Or they hear only selected aspects of the explanation and fit it to their observation, which is different though neither they nor the teacher realize this. In the following section, I provide an account of mediating circumstances that may have interfered with students’ understandings.
Based on my observations, I identified a number of influences that mediate students’ observation sentences and explanatory discourse relative to the demonstration. The influences, however, cannot all be separated entirely because they interact. For example, in this course, students use force talk to explain why the stool rotates. At the same time, their force talk also fits with force talk related to the phenomenon of precession (the circular motion a spinning top undergoes because of the gravitational pull). In the data sources assembled as part of the research, one can identify a number of influences that mediate what and how students learn from demonstrations. These include: (a) students have difficulties separating signals from noise, that is, they do not know which aspects of the display they need to focus on to understand the teacher’s accompanying or following theory talk; (b) when students come to see a particular demonstration, they bring with them different discourses that frame their descriptions and explanations, which may be inappropriate for and mediate the development of a discourse suitable for the situation at hand; (c) other demonstrations students have seen mediate their development of a discourse because of superficial similarities in images and discourse; (d) students may not be able to connect the different representations that are implicit in the teacher’s theory talk to other aspects of their knowledge about physical systems; (e) the low priority given to constructing and understanding phenomena compared to being able to get the correct results on numerical tasks affects students’ engagement with the demonstrations; and (f) a lack of opportunity for students to engage in a discourse about the demonstration to test the appropriateness and suitability for describing, constructing, and explaining phenomena. In the following subsections, I articulate issues and aporias concerning each of these mediating influences.

Separating Signal from Noise

For demonstrations to work at all, students need to perceive what the teacher intends them to see so that his presumably correct explanation provides a plausible account for what the students actually perceive. However, the videotapes show that there are frequent situations in which it is not clear to students just what Toby wants them to see. Nor is it clear whether what they have actually seen is to be taken as a relevant signal or as an irrelevant noise. Here I use the terms signal and noise, which are the standard concepts for people concerned with information and information transfer. They are appropriate here, because they make crucial distinctions that are at the heart of the problem with which scientists and our students have to wrestle. In one situation, for example, Toby throws a beach ball repeatedly to students and instructs them to throw it back in a certain way. The observers in the room find out only long after the demonstration that it has not shown what Toby wanted it to show: An object that experiences a force away from its center of mass will exhibit both translational and rotational motion (see also the investigation with the baton described in chapter 2). Whereas Toby knows that the demon-
CHAPTER 1

stration is not working as intended, the students do not and cannot know if they are observing a signal or noise.

In their explanations for what they have seen in the posttest demonstration with the spinning bicycle wheel, students’ notes indicate that they are divided in their observation. During the demonstration, a slight movement of the person on the turntable can be observed, which is possibly due to the axis of the wheel not being completely horizontal. In this case, physicists would explain that there is a component momentum parallel to the axis of the turntable (a position of the bicycle wheel between the two extremes shown in Figure 1.3), which reacts by turning so that the overall momentum remains zero. The analysis of the posttest shows that five students—all normally high or very high achieving—do not observe any movement—three students have predicted this, while two have changed between prediction and observation. They consider the wiggles as noise on top of the real signal, no motion. Eighteen students state on their posttest that the demonstrator–table system has moved—eight of them adding that the movement has been “little” or “slight.” These students maintain that the person has moved, even when this experiment is contrasted right away with a situation where the axis of the spinning wheel is parallel to the turning table’s axis, which gives rise to several complete rotations of the turntable in the direction opposite to the bicycle wheel. For these students, the wiggles are the real signal: they have observed significant motion. The uncertainty whether what she has observed is to be interpreted as motion or stationary state is apparent in Karen’s account of the situation: “The wheel that he was turning, spinning, and that he was fairly much stationary but he moved slightly and I wasn’t quite sure what the actual movement was.”

After the fact and by closely watching the videotape, I-analyst can say that the stool has moved about one-eighth of a turn. From the perspective of the uninitiated students, it is not clear whether this is actually noise or signal. After the lesson during a moment when he reviews this demonstration on video, Toby shows awareness of the small size of the movement but notes that he has told students about the friction that has slowed him down. In reaction to the test item, where the angular momentum of the wheel is perpendicular to the table’s axis, Toby suggests that some students may predict to observe rotation. However, he suggests that all students should be able observe that there is no rotation and he expects students to use an explanation of the type, “The axis of the wheel was horizontal; hence the man did not spin about a vertical axis.”

During interviews, I later ask those students who have seen and described the movement as insignificant how they might defend their claim in the face of the fact that so many of their peers have seen the demonstrator move. In all cases, the students continue to maintain their description of the motion as negligible. For example, Jon contrasts the two situations, with the wheel’s axis perpendicular and parallel to the stool’s axis. In the light of the movement with axes of bicycle wheel and turntable parallel, he interprets the other movement as non-significant.

An explanation drawing on students’ inexperience in separating signals from noise, or worse, invoking “low ability,” cannot be satisfactory as I show especially in chapter 3 concerned with a phenomenology of perception. Developing the com-

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petence to separate signals from noise constitutes the daily work of scientists and engineers alike. They, too, struggle with separating signal from noise prior to being thoroughly familiar with the phenomena under study, at which point they make rapid assessments of what there is to see or not to see; it may take weeks or months before they get to this point (Roth, 2003). Such interpretations are impossible to make out of context, for signals of the same order are significant in one, but simply noise in another context. That is, the nature of a data point—signal, noise—is not given in any absolute sense but depends on the theory. That is, any demonstration risks not being perceived in some intended way that supports and is explained by, some specific concept or theory.

Mediating Discourses

Students always already bring to the classroom ways of talking from different, out-of-school and in-school contexts. These everyday, mundane ways of talking enable, envelope, and ground any new ways of talking, that is, scientific discourse. I-learner never only talk one language; and talk about any physics topic will involve words, sentence structure, topical organization, and so forth that also have currency in mundane language. Given that Toby’s demonstrations and the posttest have been in the context of a physics course, students might be expected to draw on discursive resources appropriated in this course for explaining what they have seen during the demonstrations. This is evident during the demonstration featured in the opening vignette when Andy invokes forces. During the test situation, seven students explicitly draw on the terms force, torque, and action–reaction systems to articulate an explication for what they have seen. The results on the test suggest that many students bring into play previously appropriated language concerning Newtonian mechanics for interpreting what they saw. The very fact that they find themselves in a physics course makes it likely that they inappropriately find relevance in other physics discourse involving phenomena with some external similarities (Roth & Duit, 2003). For example, Jon says:

Because if you use the rule, the acceleration and momentum is going through him and it’s perpendicular to where he’s standing. So a force is not applied in this vertical axis but it is applied in the x-axis, so if there’s not force applied in that direction you wouldn’t expect him to move.

Jon also invokes Newton’s third law according to which every action is associated with an equal but opposite reaction to explain his observation. Such explanations appear especially appropriate because there usually is some movement whenever the wheel is accelerated so that the acceleration of the wheel and the beginning of the person’s motion coincide. Aubrey suggests, “Because it is a closed system. The force of the wheel caused his body to turn. Every action has an equal and opposite reaction. Therefore his body turned in the opposite direction to the spinning wheel.” Others combined discourses from other domains including torques and their magnitude as a function of an angle.
Mediating Observations

During the posttest, students predict and interpret events on the basis of prior experience. They used “mental images” as resources in their predictions, interpretations, and explanations. However, these images and the predictions students derived from them often are inappropriate in the context of the posttest questions. For example, both Christina and Karen suggest that the person on the frictionless table should turn although the axis of the spinning wheel is perpendicular to that of the table. Asked to explain, Christina responds, “Partly because I have seen Toby and partly because of my own experience with my study chair. . . . Mainly knowledge, that I had seen it before.” Karen explains,

I thought there would be some movement, because I had seen it before but I couldn’t remember what the movement was. I sort of missed it a little bit because the movement was so slight, so I wasn’t quite sure what was going on, so I couldn’t really explain it.

Students’ explanations of the phenomenon are mediated by a number of other demonstrations with surface similarities even if these other demonstrations occurred at a later point in time. One mediating effect is produced by a rather spectacular demonstration during which a spinning bicycle wheel is suspended from one side of its axle without falling to the ground, precessing around the rope that suspended it (Figure 1.4). On the surface, the situations in Figures 1.1 and 1.4 appear similar: a bicycle wheel is held parallel to the ground. However, whereas in Figure 1.4 the wheel is free to pivot vertically about the point of suspension, which leads to the precession producing torque; the bicycle wheel in Figure 1.1 is fixed and is not allowed to move downward. Structurally these are different situations so that a different explication has to be chosen. These images and Toby’s associated

![Figure 1.4](image-url)
talk provide students with resources for explaining the demonstration they have seen earlier and which reappears during the posttest. Thus, students explain, “The two torsional forces acting on him caused a resulting force which turned him to the left” [Andy], “The torque on the spinning wheel forced the man’s body around with enough force to rotate it” [Allison].” “He moved in this direction because of precession” [Brett], and “Precession only occurs when something is rotated around two axes at right angles. The wheel is only rotating around one axis, so no other movement occurs” [Dean]. Karen’s explanation is exemplary in one sense. She draws on the discourse that the teacher previously has employed during the precession demonstration and invokes the existence of two forces, the different directions these forces need to have relative to each other, and the resulting movement of the system.

Students also make explicit reference to a sketch that has been provided with the test item. Dean derives his explanation from the teacher’s talk, his perception of the wheel, and the arrows the teacher has drawn on the blackboard as part of his explanation of the precessing bicycle wheel:

I took a lot of it just from what Mr. Mory said and what he showed us with the three axes joined at right angles, so with the wheel being rotated in front which is one axis and then also round the second one. So the third one is straight up and down so you’re spinning around that way, so you have to spin one way or the other and I didn’t know which way. So, yes, from what he said there’s a force somewhere that tends to make it turn around a third axis.

Switching Representations

From Toby’s perspective, students should have been able to show the direction of angular momentum by means of an arrow in a pencil drawing. Students already have been familiarized with the right-hand rule and repeatedly have been exposed to Toby’s explanations using it: when an object moves in the direction of the curled fingers of the right hand, the thumb points in the direction of the vector that physicists use to represent angular momentum, angular velocity, and so on (Figure 1.2). In these situations, the videotape features Toby showing students the direction of the vector using the right-hand rule, and writing the algebraic equation from which the equality of magnitude can be taken. Toby even says, “This was going in that way, rotating that way. Let me see, vector upwards.” He accompanies this statement by a hand movement showing the direction of the “that way” with his curled fingers, followed by the thumb pointing upwards into the air.

But Toby does not draw on a standard convention for representing vectors: that is, draw arrows whose lengths are expressions of magnitude and whose orientation indicates the direction of vector quantities. Without the actual drawings, however, “vectors” may be just another term that has no or little meaning; that is, students might use the notion for their own intention or might fail to integrate it into their discourse about the situation.
Toby’s discourse (see opening vignette) is composed of many elements from different domains; they provide, as I show in chapter 5, different maps or lenses. Here, because the elements of the different lenses appear together as if they are part of one and the same lens, they lead to confusion. There are descriptions of: events happening before the students’ and teacher’s eyes; how to find the direction of the angular momentum vector from the observation (right-hand rule according to which the thumb shows the direction of the vector when the fingers are curled in the direction of the wheel’s motion); a vector as radial rather than a “real” one; intentions normally absent from physics discourse (“there’s no way that I’m going to let my body rotate”); and of the “darn friction in that chair” which interferes with his presentation of the ideal world of physics. These descriptions refer to different positions in and dispositions toward the world. The right-hand rule (depicted in Figure 1.2) integrates these dispositions. The physical experience that can be observed, measured, and manipulated constitutes one of these worlds. The curled fingers pictorially represent the rim of the wheel—pointing in the direction in which the wheel turns—denote an aspect of this world. The thumb stands for an object in a very different world. It is part of a discourse physicists use to describe and explain phenomena. The thumb stands for a vector, a mathematical quantity which itself can be depicted and represented in a number of ways, some pictorial (arrow of specified length and direction) others in what seems more abstract ways as letters, matrices and so forth. Whereas teachers exchangeably use these different ways of presenting, they constitute different pieces of knowledge for the students. These ways of denoting the theoretical expressions do not make sense to students because the expressions do not fit into the already everyday language patterns they are familiar with and therefore do not fit into the inherently meaningful lifeworlds that the students inhabit. The posttest and the associated interviews show that students do not integrate these worlds and their descriptions to an internally consistent framework.

Mediating Context

The events in which students participate and constitute make sense in their nature as socially and societally organized. I participate in lessons as teacher or as student, and what I hear, I hear through the lens of participating as I-student or as I-teacher. That is, although my actions are embodied in the sense that only through them I can act—even talk requires work—they also are mediated by the nature of the current activity. An action presupposes the nature of the activity; but it is only through concrete actions that the activity (e.g., schooling) is realized. Therefore, the ongoing event and specifically the currently relevant entities in and aspects of the setting mediate the production and “consumption” of an action. This activity, involves others; even my (material, discursive) actions are such that I can always provide reasons for them, which means that their intelligibility is inherently oriented toward others. First and foremost, students participate in schooling, which provides them with resources to go on to university or with constraints that prevent them from being accepted in some program of their choice. This rather than questions of
knowledge mediates what students do as part of their physics course, including note-taking during demonstration, studying without paying attention to demonstrations they have seen, and so on.

Even the shortest excerpt from a classroom videotape serves to illustrate how (discursive) actions both mediate and are mediated by the context; that is, in each situation is produced in its singularity but also reproduced as a type of situation. In the following excerpt from the introductory episode, Andy asks what will happen if the teacher holds the bicycle wheel over. Toby responds suggesting that he wants the student or students think about (turn 02).

01 Andy: When you turn this ((points to the wheel)) over will that do it in the opposite direction, which will also help you stop? When you turn that over one-eighty degrees?

02 Toby: That’s what I want you to think about, why, when I turn it over, did I reverse? Now I should keep spinning if it wasn’t for the darn friction in this chair.

In this situation, one person asks a question, but the other person turns the question around, which suggests that the person who has asked also is made responsible to provide an answer. Immediately afterwards, Toby moves on to attend to and talk about something else without waiting for an answer. Looking at this exchange without knowing the two individuals but only have the utterances available, I-analyst might not immediately discover that the person asking the initial question is a student. But the response provides me with resources for hearing it as the response of a teacher—just imagine a student answering the teacher question “Why are you late?” or “What is the answer to this question?” by responding, “That’s what I want you to think about.” Thus, in acting as they do, Andy and Toby also reproduce a typical teacher–student interaction (which researchers then often describe and explicate in terms of power relationships). Other aspects of the setting also mediate what students hear, how they hear it, and how they attend to what they hear.

In the videotapes from the classroom, many demonstrations are flagged and prefaced with some remark, which suggests that students would not be accountable for them on tests. Toby wants to raise interest and wonderment. However, over the six weeks in this classroom, I arrived at the conclusion that there is a very low priority on understanding from demonstrations. Toby and his students appear to assume that they remember the events in the case of a test or exam (e.g., “I just watch and soak it all in,” “We just observe what happened”). In such instances, many students diminish their active engagement (e.g., “I mean you immediately don’t write any notes down or anything, we will just listen to this and have a bit of enjoyment”). As to the importance of demonstrations flagged by Toby as being for interest, Rhonda’s response is indicative and representative of many I receive: “I probably wouldn’t concentrate on that as much, like I would take notes on what he was doing but then go back to, maybe just use the other stuff if I wanted to know how something worked. Some of it I don’t think I really need to know.”
Students’ notebooks make no reference to any of the demonstrations, as if these are not useful resources for doing well in this course (“Examples were good there didn’t seem to be enough behind them they were just examples of like, of what it relates to”). Where there are any records of students’ note-taking during demonstrations, these are always formulas, equations, and calculations that Toby notes on the chalkboard; I cannot find in these notebooks descriptions or other forms of representation of what Toby shows or the explanations he gives. Problems that require the calculation of missing quantities, and any information that might pertain to these activities, are the few things students always copy down from the chalkboard. In the recorded interviews, some students lament the fact that demonstrations do not lead to better understanding; thus Christina says, “We didn’t sort of work out exactly the physics behind what was happening and why it was. I think it would have been better to do that.”

In this class, there are few discussions, which, from a sociocultural perspective, provide students with opportunities to talk, and in talking, to test their own understanding. But neither students nor Toby appear to be willing to create such situations, that is, exchanges during which alternative explanations and discourses are evident. Toby is quite happy to present his demonstrations without interruptions. He repeatedly tells me that his own interests are the primary determinants of what he does in his physics class. As a result, he is so engrossed in demonstrations that he forgets about student learning: “It’s only when sometime down the track I get a wrong answer in a test or I get a wrong comment somewhere that I realize that what was clear to me, wasn’t clear to them.”

When students do ask questions, Toby frequently does not take the time to assess what might motivate the student to ask this particular question at this time (Toby always is willing to listen and talk to students after class, or to be called at home by students when they experienced difficulties with their textbook problems.) The exchange with Andy is typical. Andy provides an alternate description and explanation for the system, including talk about forces. Toby, however, simply turns the question around and then shrugs Andy’s comment off, “I am not even mentioning forces.” During the posttest—which features the same phenomenon—nine students employ force to explain the phenomenon. The episode with Andy illustrates that an important opportunity may have been missed: for students to know and know about physics, for Toby to know about student knowing. The test results show that his comment, “I’m not even talking about forces” is insufficient for students to abandon force talk in the context of this demonstration. It is not far-fetched to think that an open discussion may have encouraged more students to join Andy, and therefore may have provided Toby with an opportunity to recognize the extent of this inappropriate discourse.

As I-author sit with the students in the course listening to Toby, they appear to be content that Toby does not ask them to talk about the phenomena. During the six weeks I spend in the classroom, there are few moments when students engage Toby, and when someone actually asks a question, then he or she always comes from a small subsample of the class (Andy, Christina). Some students also want to avoid embarrassment. They do not ask questions because it might be about some-
thing they ought to know. They fear Toby interprets such questions as obstinate behavior and may become unkind (“I think everyone kind of gets scared that if they ask Mr. Mory, he is going to yell at them or something like you sort of think maybe it is something that you’re supposed to know”). Another student cites specific instances where Toby had called on her, and each time she felt it was to embarrass her (“he wanted to embarrass me or something”).

**GAP BETWEEN DEMONSTRATING AND PERCEIVING**

Toby Mory is typical of many teachers in his view of learning and teaching as involving the process of transmission. He is atypical in so far as—based on the views of his peers and some observers—he is very skilled in conducting demonstrations and that he commands a large repertoire of demonstrations. He is very well intending, but—bringing to this teaching technique an epistemological stance according to which the world is inherently mathematical and knowledge matches this structure—overestimates what physics neophytes can see in and learn from demonstrations. Thus, he expects students to see conservation of angular momentum in his demonstration, separate noise from real signals, reconstruct the equivalence of signs across representational systems, and so forth. But Toby’s assumptions—and likely those of many other science educators—are unwarranted. Despite his efforts and skill, the students in this class do not come to understand this and other demonstrations, the conservation of momentum, or the vector representations associated with the various quantities involved.

**Teaching and Students’ Learning Aporia**

My intent here is not to criticize Toby or any other teacher using demonstrations. Rather, I attempt to understand how a very common teaching practice—the demonstration of events that are suitable to make scientific discourse intelligible and plausible—under certain circumstances fails to lead to student learning. I am interested in finding out about and understanding these circumstances. In the present context, there are six important aspects of the situation that mediate the experience in such a way that student learning of the target concepts does not come about: (a) without a theory, students have difficulty in separating noise from signal, (b) previously appropriated discourses interfere with the development of a new, situationally appropriate one, (c) the image traces of other demonstrations and everyday phenomena lead students to alternate explanations, (d) students do not construct on their own the equivalence of signs from different representational systems, (e) the overall context is such that many students did not consider demonstrations as something of importance, and (f) students have no opportunities to test whether their descriptions and explanations of the event are viable. I cannot know whether these aspects in fact caused students not to learn, nor does it permit me to say which of the aspects contributed to a larger extent. The available evidence only permits the hunch that the order of these aspects differs among students.
To know what the teacher wants them to learn from a demonstration, students need to be able to separate signals from noise: Is a wiggle in the body of the experimenter a significant motion or simply an artifact of his preparation? How can students make such a decision? My ethnographic studies among scientists show that they often spend a lot of time differentiating “blotches and wiggles” from “real signals.” Their work consists of coming to perceive the “real signals” from a sea of blips and blotches in rationally accountable and defensible ways. Thus, the decision whether a peak in a spectrum is signal or noise usually is based on theory. But if the theory does not yet exist, scientists may proceed by evolving tentative descriptions and embodied laboratory skills until a local theory emerges.

Students who watch demonstrations, however, neither have the scientific theory that the demonstration is to provide evidence for—this is what they are to learn from the lesson—nor the opportunity (or competence) to make the necessary distinctions. The students also do not have the opportunity to ascertain whether they can achieve agreement as to what they observed. Furthermore, students face similar problems when they are to learn specific scientific concepts from the laboratory activities Toby has asked them to complete. As I show in chapter 2, in these laboratory activities, it is virtually impossible to isolate what the real signals were without some notion of the theory to be learned. Thus, from the posttest data I know that for the “same” event the observations ranged from no motion to significant motion; that is, the same event really constituted two events, the event seen by different bodies in different positions and therefore dispositions. It is clear that such discrepancies can be used as topics of debates in which the teacher raises the signal versus noise issue on a metatheoretical (nature of science) level.

A traditional problem of school knowledge is that symbolic systems (numbers, vectors, diagrams) remain isolated and have no referent or relevance to anything else students know. Students learn to manipulate symbolic structures without referential content and are not provided with opportunities to integrate those symbolic structures that can be used alternatively to describe the same system. Students in this study know that vectors are quantities with magnitude and direction, have had previous experience in writing vector quantities as underlined letters (e.g., \( \underline{v} \) for velocity), using arrows to represent vectors, and using fingers to represent directions (“right-hand rule” to find the direction of a magnetic field generated by an electric current in a wire loop). But I assume that all this knowledge exists in the form of separate pieces of memorized information—it is not surprising that some science educators talk about “knowledge in pieces” (which I think to be nothing but an artifact of schooling). Toby has used two of these representational forms, vectors (e.g., \( \underline{L} \)), gestures (e.g., Figure 1.2), and words (e.g., “right-hand rule”), but when asked, students do not use arrows to indicate the direction of angular momentum including the normally highest achieving among them. Toby, though, has behaved in an ordinary way for scientists. Scientific discourse does not referentially isolate but integrates different forms of representation in situationally appropriate ways; as I show in chapter 5, science works because it layers perspectives and maps. The present students do not have opportunities to participate in science talk that uses multiple modalities in the way their teacher, in the taken-to-be-
appropriate ways, practiced it. Consequently, they fail to provide appropriate responses, namely those that the teacher expects them to give. Using different forms of making an investigation present again and developing ways of communicating what can be articulated is the topic of chapters 6 and 7.

The students do not develop the competence to talk about the phenomenon of interest in a way compatible with scientific canon. From the perspective of many students in this class, there is no real need to carefully watch demonstrations and to attempt to understand them. In this course, word problems are the main evaluative tool. Students can get these problems right, or at least garner enough partial credit to get a reasonable grade without understanding what the problem is about, or whether it refers to anything at all. Students describe strategies for achieving good marks without conceptual understanding. In this context, students have little incentive to see what the demonstration is to show and to develop competence in the associated physics talk (i.e., to develop an understanding). But even if students try to make their own frequently alternative descriptions the topic of conversation, Toby does not engage them and brushes off any comments that do not fit into his plans. Students therefore have no means or opportunities to assess in which way their talk is inappropriate because, from a language perspective of knowing, competence in “talking science” requires participation in scientific discourse.

Toward a Social Praxis of Science Learning

My concern in this chapter lies with understanding how a specific teaching practice is mediated by particulars of the setting. My ultimate goal is to arrive at one or a series of recommendations that could be a starting point for an action research project. A (social) praxis view of knowledge provides teachers with a new referent that entails changes in actions and classroom climate more conducive to learning from demonstrations.

From a received perspective on science teaching, Toby has done many things appropriately. A received perspective of knowledge treats it in modular form. Words (concepts) “have” “meaning” and refer to real objects. Looking at real objects and events provides a direct view of the concepts. Through observations individual students are enabled to see the underlying structure. The teacher only has to provide the correct labels (we note that this is also a central part of other teaching strategies such as the learning cycle). For example, in a classical perspective, a reasonably intelligent student should be able to “put together” the idea of the thumb up into an arrow and the content knowledge required on the test, given the knowledge that vectors have magnitude and direction. From a discourse perspective, any one of the three ways could be appropriate as part of the discourse about angular momentum of the bicycle wheel and replace the other two. The important difference is that the alternate signs and symbols can only be learned in praxis, for whatever sense is attributed to them is always mediated by the activity of which they are part. The thumbs-up gesture and utterance are aspects of an in-joke, inherently a joke that only insiders understand; but I am an insider in my lifeworld, culture, or familiar settings. If I do not get the joke then it is perhaps because I am not
inside the group that defines through its practices what is in and what is not. Teachers therefore may take a perspective in which all activities, doing experiments, talking about design, explaining phenomena, constructing re-presentations, and so forth are considered social practices; these practices are realized in concrete human praxis. These are shared, developed, and negotiated within specific communities of knowing.

A social praxis perspective might help Toby to view learning as one of participating in the production and reproduction of perception, manipulations of the world, separation of signals from noise, talk about phenomena, constitution of phenomena through adjustment of discourse, representation of phenomena in terms of vectors, and construal of invariants (not finding or discovery of invariants). A social praxis perspective might help Toby to recognize that to make sense together, students have to engage in and develop practices together, be able to negotiate understandings, and repair discursive trouble (misunderstandings, errors). It might help him to recognize that in his classroom, and especially around the demonstrations, there were a lack of opportunities: (a) for discussion in which he, Toby, comes to understand students’ understanding (or lack thereof); (b) for the students to check whether their own talk about the phenomena is shared with others, is viable and fruitful, or whether it needs to be changed; and (c) for checks whether what students construct as a phenomenon is from a scientific perspective, the phenomenon to be of interest or simply noise.

When teachers adopt a social praxis perspective, their learning environments changes. These are then no longer considered places where experts transfer their knowledge and products to less knowledgeable others. Rather, learning environments become places where all participants engage in developing new and common social practices (doing practical things, describing events, talking theory, etc.). These new social practices develop out of previously existing ones if they are to be robust and connected instead of piecemeal. There is evidence that such an approach works. I have read about how Swedish designers of a computer program to be used in a printing shop got together with the workers. Rather than imposing their computer-based work places on users, these design engineers of the new generation begin their work with mockups to establish a common discourse between professional designers and future “users”; they establish common ways of looking at, interacting with, describing, and theorizing a world that they make and take to be in common. In the process of talking about relevant artifacts, this common discourse begin to change as the artifacts evolved; and with the evolving artifact, designers’ and future users’ mutual understandings changes so that in the end, an intelligible and functional workplace emerges.

One of the things teachers like Toby may want to try is to present a demonstration, followed by student discussion, and presentation of a received framework with vector representations both in parallel and in orthogonal orientations. Keeping the different representations (in chapter 5, I suggest the analogy of lenses and maps) separate and show how science means to coordinate them may assist students in developing more consistent discourses about specific phenomena. This may help students in the present context develop explanations in which the conser-
vation of angular momentum, the relationship between the relative angular velocities (moments of inertia), and the influence of friction on the system are important resources—there is evidence that such an approach works. I have experienced first-hand how seventh-grade students engage in a lengthy argument about the outcome of a tug-of-war between themselves and the teacher (me) who was assisted by a block-and-tackle. In this case, students and teacher move from talking about the event and the actual block-and-tackle to the chalkboard where their discussions evolve around representations, both simpler and more convincing than the actual artifacts.

Teachers can learn by adopting a social praxis perspective of teaching and learning physics, as captured in the following episode. After the posttest on rotational motion, one of my researcher colleagues says to a group of students, “thumbs up” and gives them a thumbs-up gesture (Figure 1.5). The students looked at him in a perplexed way, evidently not understanding what his comment can or shall mean; they did not get the intended joke. Although a joke explained no longer is a joke, here is how my colleague intended it: Because the right-hand rule can be used to answer most of the questions on the posttest, he finds this everyday expression humorous. The thumbs-up gesture resembles the gesture that embodies and articulates the right-hand rule (Figure 1.2), so that it can be understood as making an oblique reference to the answers on the test. However, what the speaker did not realize is that to understand this humor, one has to be part of the particular discourse community in which the relationship between the gesture and the phenomenon is taken in a very particular way. This in-joke is comprehensible only to those who are already competent participants in the community (fluent speakers). And it requires seeing the thumbs-up as denoting the right-hand rule rather than a thumbs-up. That is, the joke resides in the crossover from the everyday domain to the specialized physics domain, where it has a second, very different signified.

When teachers understand that knowing means knowledgeably participating in such conversations rather than carrying around stuff in the head that can be regurgitated when requested—on tests—then they have made a big step toward a social
praxis perspective. It is then easier for teachers to engage students in conversations and active exchanges, because this is where knowledgeability comes to be enacted. Most importantly, teachers no longer ought to think in terms of knowledge as something stable that is in and can be transferred to students’ minds. Knowing is doing, and in doing I articulate knowledgeability for others. Equivalently, it is in and through their actions that others make their knowledgeability available to me. That is, perceiving others’ actions is all that we ever have available, never any knowledge, conception, or conceptual structure. Participation in praxis, therefore, means participating in exhibiting my own knowledgeability and being confronted with that of the other. I do not have to go one in deeper, below the skin, and even less into the brain case of others.
CHAPTER 2

APORIAS OF ORDER PRODUCTION

In chapter 1, I articulate what students expect to perceive, how they articulate their perception, and how they explain what they have seen after observing an event. There are a number of situational factors that mediate how students orient themselves to a demonstration and what and how they can see in it. In the case of demonstrations, someone else (here the teacher) produces some spectacle and the audience is asked to observe and perceive the spectacle in an often-unspecified specific way. Chapter 1 shows that the student audience does not see what it is supposed to see, which requires knowledge of the knowledge to be learned, and therefore does not learn from the demonstration. Perhaps students learn when they produce the spectacle themselves? To find an answer, I studied all the videotapes taken while students engaged in investigations. The following narrative exemplifies what I can see when students engage in laboratory tasks.

To assist in learning about moment of inertia, Toby Mory, the experienced physics teacher from chapter 1, instructs his twenty-four students in his twelfth-grade physics class to conduct an investigation. “We have here an assemblage of various cylinders and ball bearings of two sizes. We’ll be rolling these on your benches and you don’t need to have a great slant, two diameter ball bearings. Solid, solid cylinders, we got at least two diameters; hollow cylinders, we have a couple of different diameters and each of those will roll.” He shows each of the objects as he instructs students what to do and adds, “I really want you to compare something moving down the bench without rolling. It seemed to me and I haven’t tried that before, that if I can make a trolley light enough of a bit of balsa and I bought a few little toy cars from K-Mart.” He shows to his students the chassis of a toy car and then continues, “We won’t take into account the turning of the wheels because they are insignificantly puny. This would give us the cylinder sliding, frictionless in effect, as compared to rolling, cylinder and solid. I really want you to tabulate what observations and conclusions you get. It will be mostly of a qualitative nature, hardly quantitative. Don’t measure, don’t stopwatch. Okay? And you are making comparisons, and you are looking for patterns and ideas, and I don’t think that any of you will get all of the patterns and ideas that you could get out of this. That is up to you to prove me wrong.” Subsequent to these instructions, Jon, Rhonda and Sean—much like the other five groups in the class—collect their materials, raise up one side of a desk by placing books under its legs on one side, and begin their investigation (Figure 2.1).

Sean places a medium solid cylinder on the chassis, releases it down the inclined plane, and describes the motion as “slow acceleration, slow velocity.” He
takes the cylinder off the trolley, rolls it down the incline and describes the resulting motion, “That would have been parabolic, the acceleration, not acceleration but the displacement.” Rhonda, speaking at the same time, corrects, “You mean the distance?” After rolling the large solid cylinder, Sean concludes, “It has constant velocity when it is not rolling.” Sean and Jon roll several other objects alone and on the chassis, commenting “It’s much the same” and “they are all pretty much the same when they are rolling.”

To the outside observer, the three appear to have “discovered” their phenomenon. They become playful and begin to interact with other students. Although the outside observer sees (and hears) that the trolley with the cylinder accelerates down the inclined surface, contrary to Sean’s claim, the three students do not appear to perceive the motion in the same way. After twenty trials, Sean is ready to draw some final conclusion. He selects the very first set up again and utters, “This is at constant velocity.” But then comments on the outcome of the experiment, “What happened there, mate?” Jon responds, “It accelerates?” Sean repeats the experiment and, after observing the same outcome: “What happened to my first theory?” “What theory?,” Rhonda questions, and Jon responds, “Let’s see what happened to it.” After another trial, Sean suggests, “They all accelerated, it’s probably the wheels.” “They’re a bit crooked,” Rhonda adds and Jon chimes in, “The wheels always are on these little carts, they never used to work in primary school.”

At this point, Toby announces that he wants students to arrive at a conclusion within the next minute. The three students quickly run a few more tests. At first they test Sean’s proposal that the mass of the objects makes a difference by following Jon’s suggestion to race two objects at a time. The results of two different combinations of solid cylinders do not yield the significant difference they are expecting. Before the teacher stops the activity, the three get in two more runs with different combinations of a solid cylinder against a hollow cylinder while holding the radius constant. Sitting down they agree: “the solid accelerated faster.”

This episode points out at least four important aspects relevant to the question, “What do students learn from laboratory activities?” First, the three students had
constructed a phenomenon after the initial few runs: *Sliding objects move down an incline at constant velocity, while rolling objects accelerate all the way down.* It is only much later that they deconstruct this phenomenon (Sean’s “first theory”) as an artifact attributable to the wheels of the trolley. Second, the three students have constructed a phenomenon that is incompatible with that which the teacher wants them to “discover.” Although the three manage to deconstruct their phenomenon before Toby calls an end to the activity, I observe many instances where students construct phenomena that are incompatible with a legitimized legitimizing perspective—e.g., Christina has collected data that disproves Toby’s theory about rolling objects. Third, the construction of a phenomenon appears to be bound up with students’ embodied material practices and language. Students’ descriptions, manipulation of material and the phenomena they construct are mutually constitutive and depended on each other. And fourth, the students do not see what the outside observer sees when the chassis is loaded with the medium hollow cylinder accelerated down the incline. My interpretations of the laboratory activities in this twelfth-grade physics class lead me to *order production* as the core issue in understanding just what students learn from laboratory activities.

In this chapter I provide first answers to the questions, “How do students construct a phenomenon?” “What is the relationship between phenomena and students’ material and discursive practices?” “What is the relationship between the teacher’s instructions and students’ actions?” and “How do students know that what they have seen and done is what the teacher wanted them to see and do?” This articulates a first understanding of the relationship between what students see when they do laboratory experiments and what teachers want them to see, and the relationship between laboratory instructions (written or spoken) and students’ actions in laboratory activities. These are the central themes of this book, which I further articulate and explicate in subsequent chapters.

The central purpose of laboratory activities is the collection of data from which, through ordering and making inferences, students are to construct knowledge. Ordering objects and events in the field of vision is not a unique and unambiguous process: it can be done in different ways, leading to different phenomena, which themselves can be interpreted in a variety of ways. Although the context of the activity in my opening narrative is constrained—Toby has selected the objects of investigation, has suggested the inclined plane, and has suggested that students look for differences—students do not discover automatically what he wants them to discover. From his perspective, watching objects roll or slide down the inclined plane should make it easy to construct this series of inferences: As an object moves down a plane, its potential energy changes into translational kinetic energy and rotational kinetic energy, which is a function of the shape, which influences the inertia.

Out of six groups doing this investigation, only one independently arrives at a result consistent with what the teacher wants them to find out; another group arrives there with his help. The other four groups do not construct a phenomenon at all or do construct one inconsistent with what he has wanted—for example, Christine claims during the whole-class debriefing to have data that disprove Toby’s
theory and that radius does make a difference. The situation is exacerbated by Toby’s tendency to reject all those student-produced phenomena that did not fit his intention and to admit only those where spheres showed a greater acceleration than solid cylinders, which in turn displayed a greater acceleration than the hollow cylinders (for more on this tendency, see chapter 1). It is left to students to re-interpret their prior actions and observations and to construe one of them as artifacts.

It is apparent from my account that the group quickly derives the two descriptions that constituted their first phenomenon. Accordingly, the medium-sized solid cylinder moves with a constant velocity when it slides but accelerates when it is rolled. (Although Sean’s utterance is “slow acceleration, slow velocity,” his later actions and utterances in the lab and his statements during stimulated recall lead me to the conclusion that he probably has meant to say “zero acceleration, constant velocity.” But for the moment, because of lack of evidence from the data sources, I have to leave the interpretation open.) These two observations are generalized to become the tentative observation categoricals “It has constant velocity when it is sliding” and “They are all pretty much the same when they are rolling.” Because these observations are novel and the two construals are the result of generalizing observation categoricals, the activities constitute moments of learning.

Much ordering activity and learning is evident during the second part of the investigation. The group makes a new and discrepant observation, which disconfirms Sean’s earlier theory that sliding objects move at constant velocity, and the students evolve hypotheses that account for the artefactual nature of the observations that has led to the first theory. In the last section of the experimentation, the students generate two new hypotheses: one is disconfirmed, the other one confirmed. This resulted in an observation categorical: “solid cylinders accelerate faster than hollow cylinders.” In the section, I am concerned with how students produce order—i.e., phenomena—and how this order arises from students’ embodied practices (e.g., what is the function of the loops of repeated action).

LOOKING AT, OBSERVING AND SEEING AS

In my effort to understand students’ laboratory activity, I have found it necessary to refine the notion of “observation” when applied to students’ activities of learning from laboratory activity. I distinguish here between looking (gazing, staring) at, observing, and seeing as. When students look (gaze, stare) at some material, they do not engage in structuring activity. That is, there is no intentional articulation (carving up) of the world into things with specific aspects and properties, and no commitment to a viewpoint about the part of the material world of interest in the lesson. Observing is the active ordering and thus structuring of the world, the search for possibilities to carve the world into singularities, things (phenomena) characterized by specific aspects and properties. Through observing, a way of framing new experience in terms of previous and newly developed language, world becomes expressible and accountable (i.e., it can be accounted for). Seeing as—e.g., seeing a spinning ice skater as an instance of conservation of angular momentum—requires a particular lens and recognizing an object or event as something
that is part of the shared world, recognizing the object as such. In chapter 5, I specifically deal with the constitution of such lenses, and how they interact with the contents given to students in their primary perception.

Looking (Gazing, Staring) At

In the videotaped materials, I see many instances where students merely look (gaze, stare) at the events they produced. There are indications that learning is occurring. Following the initial observations and discovery, the three students roll a number of objects without giving any indication of whether they are in fact observing or seeing as. The video shows the three students only partially engaged in further data collection, rolling the objects while attending to other events in the classroom. This may be an indication that they merely look at the rolling objects. Interesting cases are two observations when the cart accelerates, which is inconsistent with the initial observation Sean has made. Nobody takes note of this, yet during a stimulated recall session, Jon and Sean instantly recognize that their fifth and sixth observations contradict their initial ones. The students appear to look at rather than observe in this instance. Another possibility is that they see later outcomes as instances of earlier observations, that is, as replications.

In another recorded episode, students are to investigate the motion of a loaded pipe (called “the baton,” which consists of pipe half of which is filled with metal so that the geometric center and center of mass did not coincide). Without saying a word, Arlene and Ellen strike the pipe three times, but differently, with the ruler and then sit down while their peers engage in longer but equally unsuccessful attempts at making sense of instructions and structuring events. I interpret this as occasions of looking at rather than observing. Arlene and Ellen make no attempt to frame the motion in one or another way. Their concerns hold back from producing any structured way of seeing, from making a phenomenon. The videotapes show the same behavior in two groups after they have overheard Toby commenting about a student experiment: “It is not doing as I want.” Playful behavior observable on video and re-presented in the vertical orientation of the activity maps replete with broken squares are different but interrelated ways in which looking at took expression.

When students are asked afterward what has happened and what they have observed during these moments in their experimental work, some suggest that they have been simply looking, others (among these Sean, one of the very high achieving students) that they “are pretty much soaking it all in.” Subsequent interviews further reveal that in some instances, students refrain from committing themselves to observations until they find out “what [they] are supposed to see” (Rhonda). The videotapes show that in these situations, they talk to other students to find out what they have observed or students wait until the teacher indicates what they should have observed. For a variety of reasons related to the classroom environment and especially the teacher’s reactions to their findings (see section “Students’ Fundamental Dilemma” below) students do not commit to observations anywhere in the videotapes and ultimately refrain from producing phenomena. In this case, they
engage in what one might call a mode of being in which I just tarry alongside, that is, to linger in expectation of an occurrence until something is done or happens.

Parenthetically, it has to be noted that asking students after an event what happened and what they have been thinking is laden with all the problems of events that take on a different sense when they are discursively made present again for different purposes and events. On one of the videotapes, there is a situation in which Sean clearly predicts the outcome of an event. Later, in the interview, he claims that he could not have known the outcome because “the [cart] didn’t always go straight or the wheels would get jammed.” However, the videotape shows that the group frames the problem with the cart’s wheel only much later. It is for this reason that researchers interested in the everyday mundane and work practices, rely on videotapes and interaction analysis rather than on stimulated recall of the participants. Their statements have to be taken very much with a grain of salt. It is entirely possible that the students do not describe aloud their framing so that I might draw an incorrect conclusion. However, because the activity structure is such that students are to come to a common description and agree upon a phenomenon, they have to communicate to each other what they observe. As soon as one student utters a description, others can voice their disagreement. If no one disagrees, agreement can be assumed.

Observing

In the experiment with the rolling objects, Toby expects students to make any one of a number of discoveries that show canonical physics in action. Students have to prepare the materials in some appropriate way to create events that appear significant and worthy of being reported in the subsequent whole-class debriefing. However, observation may not lead to the structuring of the material world such as to reveal the teacher-intended structure; students may in fact produce order but an order that differs from the teacher’s own. In the videotapes, the three students featured in the introductory episode (and Sean in particular) frame the first event as an instance of constant velocity, whereas they structure the second as an instance of accelerated motion. A first utterance such as “constant velocity” or “that would have been parabolic” is a tentative observation sentence, describing an evidently vague something that only with time and through processes of reification becomes a more-or-less certain object. In the context of the lesson concerned with motion, the difference between the first two observations is significant, leading to a specific finding within Sean’s group. In the same way, Andy describes and thus frames observations while observing rolling objects. It is especially clear that at this point, his first four descriptions are still apparatus bound: The fact that he describes the outcomes in different ways indicates a strong possibility for their artefactual nature.

Observing therefore is an active process by means of which an agent structures a field of experience into figure and ground; observing seeks to structure that which is not yet structured structure and if which I am aware only in an inarticulate way. The verbal description of an event then already constitutes an interpretation.
Prior to an act of observation, the field of experience is transparent, unnoticed, inconspicuous and unobtrusive. Students may look at the scene and “soak it all in” in a mode of “just tarrying alongside.” But it is through the act of observation that students separate this field into objects with properties and surrounding context. Because of the diversity of their experience, deriving from their dispositions, students’ perceptions of objects and events are likely to be different from those of the teacher (or any other representative of standard physics).

Science educators often assume that students need to state hypotheses explicitly and then test these to learn from their observations. To do this, students would need to confront their own ideas, which have therefore to be elicited and become object before they make their observations. But hypotheses require variables, and variables are exactly the desired outcomes of the activity in which Sean and his mates are engaged. This process would mean making hypotheses and therefore commitments before observations are made. Observations of scientists at work and scientists’ own self reports, have not confirmed the necessity of such explicit stating of hypotheses. Frequently, scientists pursue experimental variations to bring out some effect; these variations contain hypotheses implicitly. They discover co-variations subsequently and then investigate these in ways that holds up in their community of practice. My videotapes contain many similar situations where students construct new phenomena by means of processes where hypotheses are initially implicit in experimental variations. For example, choosing the hollow and solid cylinders for configuration, Sean and his teammates can be said to test a specific hypothesis, although they never state one in the traditional sense of the concept. The hypothesis is embedded in the design of the apparatus and therefore was enacted in the course of the inquiry. Because it is embedded though not salient, it is already part of the familiar practically understood world—which, in as a result of the figure/ground dialectics described in chapter 3, allows the hypothesis to become figure (salient structure). But to lead to learning, it eventually has to be articulated—as I show particularly in chapters 3 and 4 and again in chapters 10 and 11.

Seeing As

Seeing as denotes the activity of a person looking at a situation and perceiving a particular order. As pointed out, for students to perceive the order that the teacher expects them to see, they have to share his tacit understanding and explicit framework. It therefore comes as little surprise that, if students see an event in the way he wants them to it is only during the occasional follow-up activity. For example, regarding the rolling and sliding objects, students are asked to verify the relationship between moment of inertia and speed when objects moved on an inclined plane. They can see the material phenomenon, though not necessarily understand it in the way scientists do, because the derivation of the relationship is rather difficult. This is exactly the point that I elaborate first regarding my own perceptual experience (chapter 3) and then regarding those of students studying static electricity in a German physics class (chapter 4). Similar instances of seeing as can be
observed in the tapes, for example, after the teacher makes clear that when an object is struck at its center of mass, no rotational motion should be observed. After students return to their laboratory tables to strike a loaded pipe, they see the event in just this way. Similarly, in the previous chapter I show how students observe different phenomena in teacher’s presentations of events as demonstrations. There I suggest that with the competence to talk about events students also come to see them in these specific terms, the see them as something.

In the same vein, once students perceive a phenomenon, they see subsequent events in terms of their observation sentences. Sean’s observation “it’s much the same,” and his observation sentence about rolling objects that accelerate in the same way have to be interpreted as instances where he sees events as something, even if he eventually abandons the previously articulated phenomenon. In the videotapes, there also are examples of students who see an event as one of a class of entities. When Andy describes the outcome during the fourth observation in the same terms as the first observation, he orders it in the same class of events. Also, the fifth observation, “the same,” constitutes seeing as, the ascription of a specific event to a class of events. This then constitutes an organization of observations under observation categoricals: “This cylinder accelerates” to “all cylinders accelerate if . . .”

REPETITION, REPLICATION, REIFICATION

A phenomenon constitutes, by definition, order, regularity, a repeatable and repeatedly observable event. Regularity cannot emerge from a single observation. To produce a phenomenon, the same actions—if there are such—have to be repeated on the same objects. Students who roll an object only once cannot be sure that what they see (e.g., the winner in a competition) is actually a phenomenon, for phenomena arise from repeated observation of something. An initially fuzzy and undetermined something is produced as the phenomenon when students reproduce it consistently—prior to that moment, as I show in chapter 4, no real observation categorical can be articulated and therefore no theoretical framework. So when Karen rolls a hollow cylinder with a solid cylinder only once and then continues with another object, she cannot produce an orderly phenomenon.

In the production of order, students frequently repeat sequences of actions. However, not all of these sequences have the same purpose so that there are different kinds of replication efforts. Jon, Rhonda, and Sean attempt to replicate the sequence between their first action $A_1$ and their sixth observation $O_6$, because the last observation contradicts the first observation $O_1$. An exact replication would indicate whether the first or second observation $O_2$ of the investigation with the first object is artefactual. Here, the artifact likely is an artifact of preparation; that is, the series of events really are not an exact replication. A problem emerges for students when the same objects are used but what they perceive does not turn out to be the same and hence is taken to be different. At this time, there is not a phenomenon and order cannot yet be produced with a set of actions students consider to be the same. In the present videotapes, they frequently interpret their own actions as con-
stant but the outcome of their actions as different and possibly random. Repetition, then, may be used to produce order at another level. Repetition inherently means repetition of singularities, and therefore embodies difference (Deleuze, 1968/1994); order arises when similarity is recognized despite the differences.

In the following excerpt, Carl, Ellen, and Karen attempt to make sense of their investigation in which they compare the movement of a rolling solid cylinder and a solid cylinder on the cart. Turns 01 to 03 indicate that they have difficulties making sense because the outcomes of the experiment are inconsistent.

**Episode 2.1**

01 Carl: This one ((toy car)) is larger and faster ((a solid cylinder)). Okay ((repeats the same experiment.))

02 Karen: So, which one goes faster?

03 Ellen: I don’t think they are different.

......

04 Carl: It goes faster, the roller one

05 Karen: But before, the other one was

06 Ellen: But before, it went the same.

07 Karen: I think we should maybe take an average the best of five anyway.

In this episode, Carl proposes that the toy car is faster, Karen questions her peers as to which of the two objects they should consider as being faster and Ellen suggests that one should interpret the contradictory outcomes as evidence that the two objects are equally fast. After completing a few more comparisons (a total of 8), the three still are unsure about how to interpret the outcomes (turns 04–06). Karen proposes a way out of their dilemma. By suggesting to “do it five times and take the average,” she brings into play the scientific practice of multiple data point measurement and, implicitly, averaging (turn 07). Here, order is produced at two levels. First, there are different kinds of possible outcomes, that is, there is order at a lower level. Then, order at a higher level is produced, generated through statistical inference. In this case, the phenomenon itself is statistical rather than deterministic. They decide to repeat the experiment and select that outcome which occurs most frequently. They assume that their preparations and the observation process are identical to previous ones but the outcome statistical. After repeating the experiment a number of times, the most frequent observation (mode) is going to constitute the phenomenon. Below I show that the teacher undercuts this attempt without explanation by indicating that the event does not show what he has expected.

The videotapes show that replication with variation in the objects is infrequent in this classroom. Few groups arrange their set-ups in such a way that the phenomenon comes to be observed in an independent test that rules out some possibilities of being an artifact. One example can be seen in Jon, Sean, and Rhonda’s experiments in which they first discard mass (“the heavier it is”) as a significant variable (set up A₁₅ and A₁₆, observation O₈) and then construct the shape (solid versus hollow) as significantly determining the rate of descent (set up A₁₇ and A₁₈, observation O₉). Here, the students replicate the experiment but with a different
combination of objects. In the first case, the fact that they make the same observation (observation O₈) despite the variation lends support to observation O₉ₐ, “same velocity” and leads them to abandon their third hypothesis H₃. This third hypothesis has not been framed as such but implicitly is contained in the choice of materials, A’₂ (different types of cylinders with equal radius). Here, replication with variation results in a confirmation of the observation of difference, lending support to observation sentence O₉ₐ. The teacher stops the investigations before these students get to the point of explicitly stating an observation categorical. They do so during the whole-class debriefing where Sean states, “hollow cylinders accelerate faster at constant radius.”

These latter processes of independent replication, which lead to reification of scientific objects (phenomena), are those in which scientists have most experience and competence. Although there is little that distinguishes individuals in science and technology from ordinary people not working in these fields, the systematic use of repetition and independent replication in the construction of phenomena is clearly different from the often-reported confirmatory bias in everyday situations. In the present tapes, one can observe such systematic attempts of independent tests only in the case of Jon, Sean and Rhonda at the end of their investigation with rolling cylinders (observations O₉ₐ,b and O₉₉ₐ,b). A different light is thrown on the students’ work by more recent research on scientific thinking (Tweney & Chitwood, 1995), which requires researchers to take a more positive stance regarding human use of confirmatory evidence. In contrast to the usual focus on confirmation bias as a reflection of the limits of human cognition, the evidence suggests that a confirmation heuristic is one of the highly functional means by which knowledge is made possible.

**VARIATIONS: ARE THEY SIGNIFICANT?**

The work of differentiating blotches and wiggles from relevant signals constitutes much of scientists’ situated inquiry. Their socially and materially situated, cultural historically mediated work consists in producing “real signals” from a sea of “blips” and “blotches” in rationally accountable and defensible ways. This is almost never made clear in science education (teaching or research). Why is variation important? At what point do I become aware of a variation as variation?

It is evident now—based on the results of the phenomenology of perception and neurophysiological experiments—that my own mobility and change are essential aspects of the material objects I know. Fixing the image of an object to a specific area on my retina makes the object disappear; it no longer exist form me (Roth, 2005a). Movement and change establish things in their environment and allow them to appear in their variant and invariant nature given the differences of the conditions that are brought about by my voluntary and involuntary movements. It is only because of variations, brought about voluntarily and involuntarily (e.g., the saccades of my eyes), that I actually can perceive the world and therefore learn and know anything at all.
The production of order (phenomena, observation categoricals, construal) often requires that students make some commitment as to whether small variations are relevant and significant or whether these are random errors. In the rolling, Jon and his mates interpret the difference between the first observation $O_1$ and the second observation $O_2$ as significant, leading to a construal, that is, the perceptual and verbal articulation of a phenomenon. Students in another group sometimes repeat an experiment but fail to replicate the observations because they interpret small differences as significant. Rather than interpreting the outcome of the races between a large and a medium solid cylinder as essentially the same with small differences as artifacts due to differences in the preparations, they interpret the sequence of actions that constitutes their preparation as essentially replicated but the outcome as different. They do not arrive at a consistent result but pursue another avenue (“What else affected it?”) and decide to investigate the effect of radius on the motion. At another table, students interpret similar differences as negligible, which permits them to construct the outcomes of experiments $A_{15}$ and $A_{16}$ as “the same” ($O_{39a}$) and “equal velocity” ($O_{39b}$).

Most students in this class do not evaluate the significance of variations. Even within the same group, small variations are found to constitute significant differences at one moment, while only minutes later, the same difference is interpreted as not significant. These observations contrast those of sometimes much younger students in a variety of open-inquiry learning environments where there are many opportunities for students to familiarize themselves with the objects of their inquiry to assess whether qualitative and quantitative variations are significant or not. That is, extended investigation within a particular context, and repetition and replication of investigations allow students to develop an understanding of variations that is acceptable and permissible, and those that are significant and constitute differences to be accounted for. Such familiarity is important for scientists and engineers, for without having experienced a particular setting even experienced individuals in these fields cannot assess the significance of a particular variation. Thus, my ethnographic research among scientists suggests that when they work in a new context, new variables emerge for them in the process of becoming familiar.

**ORDERING MANIPULATIONS: FOLLOWING INSTRUCTIONS**

Teachers often provide students with written or verbal laboratory instructions. It is generally assumed that the relationship between a good instruction and the action it describes is simple: Good instructions are unambiguous and lead agents to do exactly what the instructions indicate. However, it is a well known fact that even the simplest instruction can be ambiguous unless I share the background assumptions and theoretical framework with those who have written the instruction—therefore the difficulties experienced in programming a VCR, in cooking a new dish following an unfamiliar recipe (see chapter 8), or in pruning trees based on the explanations that appear in a gardening book. As teachers are interested in students’ production of specific phenomena, the question therefore has to be posed, “How do students know that what they have done is what they were supposed to do?” The
following episode illustrates the relationship between a teacher instruction and the observed student actions in one group consisting of Brenda, Jon, Rhonda, and Sean.

Toby has shown students a metal pipe, one-half of which is filled with a substance so that the center of mass (Figure 2.2b) is not in the geometric center of the object (Figure 2.2a); he calls this metal pipe a “baton.” He has asked students to “mark dead center of the baton and give it a strike with, perhaps, a meter ruler. I just want you to comment later about the motion of the body.” Rhonda tries to predict what they will observe in this activity, “may be the mass, the center of mass stays in one path, it doesn’t move, like the center of gravity.” Sean looks up, “A bit like what Jim said (earlier in the lesson).” “Strike it with a ruler,” he continues and provides slight blows from the top to the pipe. Brenda, Jon, and Rhonda watch Sean change the blows’ directions, now from the side so that the loaded pipe rolls to the left and to the right, a movement that Rhonda renders in descriptive terms, “It rolls around in a circle, it’s like a fish.”

Jon picks up the pipe and rolls it down the inclined table. Sean comments, “It rolls straight.” Rhonda countered, “But if you push it, with a ruler it is not going straight” but acknowledges the straight movement Sean has brought about by gently pushing, which he comments upon by saying, “Yes it does.” Sean follows Brenda’s suggestion and hits the pipe in the middle (i.e., as I articulate it in chapter 8, he hits it in a way that he can be said to have followed her suggestion). Rhonda greets the resulting motion, “You see” and Jon comments, “It’s changing on an angle.” The teacher passes by and tells the students, “What I’d like you to do is just mark the center of strike and give me your comments.” Sean strikes the pipe and engages Toby to check if what he is doing is what he is supposed to do. “Is that working?” “You just make a short sharp shot, just as in billiards,” replies Toby. Sean obliges and makes the further observation, “It is not working,” but Toby has already moved to another group. Jon then suggests, “I s’pose. But that’s what we are s’posed to do.” A few seconds later, Toby interrupts the activity and calls the class to order.

If this were an isolated episode or an episode involving so-called “low achieving students,” many teachers and researchers might dismiss the problems it raises suggesting, perhaps, that the students have a problem because they cannot follow instructions. (In chapter 8, I analyze the difficulties of following instructions and the aporias inherent in the process through a phenomenological analysis of my own
experiences.) However, the other five groups in this class have similar experiences. Some are spinning the loaded pipe ("baton"), some roll it on the table, and some strike it from above. In fact, one might say that this group has come closest to observing what Toby has wanted them to observe. Other observers might be tempted to blame Toby for giving poor instructions. Again, this would miss the mark for one can find on the videotapes similar student behavior in situations where they have detailed written instructions in their hands.

To the observers of the episode, the four students—who represent a cross section of the class in terms of their achievement in Toby’s class—appear baffled. The four seem to be wrestling with many questions, “What does Toby want us to do? What could it mean, ‘dead center,’ ‘give it a strike,’ and ‘perhaps with a meter ruler’?” “Were they to mark the geometric center or the center of mass?,” “Which of these possible ‘dead centers’ were they asked to strike?,” “What sort of strike?,” “From which direction?,” and “What has the meter ruler got to do with the strike?” Before answering this multitude of questions, students have to begin a situated inquiry from which, because something is significant, they can elaborate just what it is that the teacher has asked them to do.

In the course of my analysis, however, this question does not seem to be independent of another one, “What is it that Toby wants us to see?” The two questions are interrelated and in fact interdependent, for, to assess what they have to do, students need to be able to assess what they have seen. The four students need to know whether what they observe is in fact what they have been supposed to observe. Somehow, students have to interpret the outcome of their actions as significant. They have to produce and articulate a phenomenon. When they come to the conclusion that they have no phenomenon, they cannot know if the problem lies in the preparation of their investigation, or in their observation. It is the outcome on the basis of which the appropriateness of an action is determined or an assessment can be made whether an instruction has been followed.

At the moment Sean and his mates predict and produce the motion of the loaded pipe, they do not know if this is the intended phenomenon any more than they know if all the other phenomena they observe are the ones they have seen. Other groups, such as the one including Arlene and Ellen, move on to other tasks, although their striking of the pipe has not produced the phenomenon that the teacher has intended them to produce and understand. Towards the end of the lesson, the teacher indicates that he wants students to verify that the loaded pipes move in straight lines when the center of mass is struck. Arlene and Ellen strike the pipe at the center of mass once, produce and thus reproduce the desired phenomenon and return to their seats. They do not appear to be impressed and take the result of their experiment as a matter of course. Although they have not produced the desired motion previously, they are now satisfied that striking the cylinder at its center of mass produces straight-line motion. At this point they are certain that what they observe is what they are supposed to observe.

Rule following implies a competence that is described in ethnomethodological studies as an “ad hoc” elaboration of rules in use (Suchman & Trigg, 1993). Accordingly, the maintenance of “any rule of action requires the local elaboration by
participants of just what the rule could mean in relation to specific circumstances of its application” (p. 167). Students in this physics laboratory tentatively elaborate, in very situated and contingent ways, what the instructions received from the teacher could mean relative to the specific context (including such things as the current curriculum, teacher’s talk prior to the activity, the conversations and activities emerging against an open horizon of possible events). If it is not clear whether what students observe is significant, that is, matches events as they would be seen by the teacher (who in an ideal situation is the representative of canonical physics), students repeatedly change their actions to produce a variety of responses from the objects under study. They “fiddle” with and adjust objects and instructions to make them fit the contingencies of the setting. They then assess whether what they observe and describe makes the event significant relative to the present context. For example, Sean interprets his actions as inappropriate (“It doesn’t work”) possibly against the teacher’s comment, “just as in billiards.” Jon’s comment, “But that’s what we are s’posed to do” opens the possibility that what they have seen is what they are supposed to see, a consequence of their appropriate prior actions. When the possibility opens for a response to be interpreted as significant, students are enabled to engage in repetition by means of which order arises through the consistency of a system’s response.

Some readers may be tempted to argue that students do not understand how to produce and observe phenomena because of ineptitude, lack of skill, or simply lack of interest. Such an approach might be a reasonable explanation if failure to produce and observe phenomena is isolated to students. However, scientists are subject to the same phenomenon when they work at the limit of what they know, or attempt to reproduce a procedure that they are not familiar with in their own laboratory (e.g., Collins, 2001). The problem with the reproduction of phenomena and its dependence on embodied laboratory practices has been demonstrated for highly trained university researchers using the polymerase chain reaction and constructing lasers. There are reports that investigators in different laboratories could not reconstruct phenomena in spite of elaborate instructions and information about the set-ups. In these cases, not seeing a phenomenon was tied up with the associated embodied laboratory practices. Michael Faraday already knew about the problems of realizing an experiment in another lab and therefore, as described in chapter 1, sent copies of his apparatus with instructions of what to do and what to look for to colleagues around Europe.

STUDENTS’ FUNDAMENTAL DILEMMA

The microanalysis of students ordering activities in a traditional physics laboratory shows how most students do produce and articulate phenomena and make sense even in this example of a traditionally taught physics laboratory. They observe, structure their field of experience and come up with reasonable results from their perspective; they also turn instructions into embodied actions through situated inquiries into possible matches between them. However, a few students who tried to refrain from making commitments necessary to construct order and thus phenom-
ena. The above analysis cannot yield the motive or goal for such student behavior. Here, the analysis has to go to a different level and investigate the larger context in which students conduct their inquiries. At this new level, the students’ fundamental dilemma emerges as shown by the following transcript extracted from a conversation recorded during the investigation with the rolling objects.

As mentioned above, Carl, Ellen, Karen, and their frequently silent partner Arlene have produced the outcomes of their races between a sliding cylinder (simulated by putting a cylinder on a toy car) and a rolling cylinder. Therefore, they decide to think about the phenomenon in statistical terms. Toby approaches the group just as the students conduct one run and observe that the rolling cylinder has a greater acceleration than the “sliding” equivalent.

**Episode 2.2**

01 Toby: I am a little disappointed keep going, keep going.
02 Karen: We are doing the best of five.
03 Ellen: It’s a little slow.
04 Toby: Try it again! Put that ((points to a weight)) right in the middle. ((Karen obliges)) Yeah, right. But I know what I’m expecting and I haven’t tried the trolleys. ((Karen conducts a race between the trolley loaded with a large hollow cylinder and a rolling large hollow cylinder.))
05 Toby: It is not doing as I want, so I’ll have to . . .
06 Ellen: What is it meant to be?
07 Toby: Well, I tell you later.
08 Karen: It’s a surprise!
09 Toby: Yeah, it’s a surprise but it’s not quite living up to expectations.

In this conversation, Toby exhibits his disappointment such as for everyone to overhear and perceive. Why does the teacher request me to “Try it again!”? Does what I have done not correspond to what I should have done?” Toby articulates that there is something he expects students to see without telling them that it is this: the objects accelerate faster when they are “sliding” than when they are rolling; instead he says that he has not tried the investigation himself (turn 04). He knows that a frictionless sliding object translates all energy into translational motion, whereas a rolling object translates some of its energy into rotational energy so that ultimately it accelerates less. The students, however, have no means to judge the outcome in the same way; they have to take events as they see them. From this perspective, “doing the best of five” (turn 02) is not unreasonable. The students’ dilemma is made salient in Toby’s assessment that the experiment is “not doing as [he] wants” and what “[he] is expecting.” He shows students that he already knows what is still concealed and withheld from them. Toby does not want to tell students what the problem is (turn 07) and they are left on their own to make sense of the objects and events before them.

Students know that the correctness of the knowable in their laboratory exercises is prefigured in advance. They are not asked to produce an order helpful to under-
stand a part of their lifeworld but to produce an order that they know the teacher is hiding from them. In other words, independently of students’ material and interpretive actions, outcomes are to be assessed against a normative order that, depending on the teacher’s own understanding, is more or less compatible with standard physics. Whereas the students have to work before an open horizon of possible positions and dispositions concerning the objects and events, they are asked to disclose the one yet-unknown possibility (dis-position, disposition) against which students’ work is judged. This form of inquiry is closed and distinctly different from the ordinary situation of scientific research, where the search for an answer to a question can arise within an open horizon of investigation.

It is here that one can situate the fundamental dilemma and difference of students’ work. While their inquiries can be within an open horizon—leading to results often quite different from those of standard science—the frame that situates their laboratory work forces them to search for a hidden order, which, to be discovered, requires students already to be a part of the legitimized and legitimizing worldview into which the activities are designed to introduce them. Such dilemmas exist even in the most well-meaning, student-centered instruction. Teachers still shape the format and content of lessons and produce fine-grained definitions of what is to be done, said, and understood. As a result, the forms of inquiry are closed and lessons are geared to the acquisition of one “right” way of seeing and explaining phenomena.

LEARNING FROM TRADITIONAL SCIENCE ACTIVITIES

Science educators sometimes claim that students’ ability to relate the scientific theory they are to learn to the phenomenon observed is constrained by differences in perception. The problem with such research is that it models phenomena as independent of human observers. From a phenomenological perspective, however, there are no “things” that are bearers of individual properties (aspects) independent of acts of perception; the thinginess of objects and of the world emerges from concerned observation and action of the human agents and the breakdown of their tools and ways of seeing. But observation is always a function of the subject’s current horizon, always occurs through a lens developed during past experiences; that is, the perceptions and interpretations are always from within a tradition, always positioned and reflecting a disposition. The presented analyses explicitly take a phenomenological perspective to eschew these problems in prior research.

Despite a lot of research and development efforts, traditional laboratory exercises have shown only limited promise: teachers use them to “motivate” students, and researchers find that students often do not develop an understanding of the phenomena that they create as part of their engagement. In the present chapter students do produce order (phenomena) during such tasks. The problem why these activities do not lead to the kind of understandings desired by science educators may lie in the teachers’ failure to use students’ understandings (whatever they are) within a sociocultural and cultural historical framework of learning. In such frameworks, differences in understanding are used in whole-class discussion to
come to grips with the variations of material actions, framing of “phenomena” through descriptions and interpretations. Teachers’ views could then be some of the many to be deliberated, as singular plural dispositions. Teachers not only would have to present that a particular view is accepted and shared by scientists, but also to students intelligible arguments for ruling out all the other views.

The events described here show that learning standard physics from laboratories is not self-evident and what students actually get from looking at a scene does not necessarily yield what the teacher intends students to see and learn. Further, following instructions is not self-evident, but requires an interaction of situated search for a match between instruction and action, whereby what one is doing is established only after the fact. Students’ assessment as to whether what they have done is what they are supposed to do, the matching of instructions to actions, has to be done a posteriori. In some cases, this may span quite some time and distance. The students’ real work therefore is this: Their praxis becomes progressively witnessable and tellable as an orderly phenomenon, that is, in the form of practices. But what they do not know is whether their situated action, though repeatable, has produced the phenomenon that relates to the context from the teacher’s perspective. Though they have produced order, they cannot know whether this is the order that makes sense and is analyzed in the legitimized and legitimizing framework. Their actions brought about by a reading of instructions emerge from a horizon constituted, among others, by the purposes of the embedding school and classroom situation, the present curricular context, and students’ previous experience. Thus, there cannot be one literal meaning of an instruction like “striking the baton in the center,” for all students take it as literal and they do what it literally means to them. Their work consists in interpreting the instruction, and enacting their interpretation. But then they also have to interpret the outcome of their action and assess whether this outcome corresponds to what they think they are supposed to see.

Teachers frequently misjudge the relationship between observation, theory and experiment; they see in theory generation little more than the collection of objective experimental and observational facts. The events in this and the previous chapter underscore the problematic nature of such assumptions. The order different students produce and articulate as they look at the “same” object varies; different orders are expected because of students fundamental dispositions that are grounded in the singularity of their bodies. If there are no opportunities for the students to discuss the origin of these variations, they simply have to accept the teacher’s evaluation of being wrong. In some situations, this has led students to refrain from generating any observation categoricals and thus phenomena. They completed a few token actions (e.g., Arlene, Ellen) or did not participate at all (e.g., Norm).

Many of those who critique traditional laboratories assume that there are phenomena and events that students should explore to construct episodic experience. However, my observations reported here suggest that it is not useful to think of phenomena in science classrooms as existing prior to students’ engagement. Rather, it is through the students’ agency/sensibility that phenomena come about. Because of their varied background, implicit theories and embodied experiences,
these phenomena more likely vary than are the same; and these phenomena are even less likely identical to those that the teacher intends them to see. Such an identity can come about only when all students and the teacher share background and experiences and above all, the same lenses (i.e., theoretical commitments). However, helping students develop theoretical commitments similar to those of the teacher is the very goal of the present lesson and not its premise.

“HANDS-ON, MINDS-ON?”

Some teachers and science educators use the expression “hands-on, minds-on” to distinguish simple hands-on activities from presumably better hands-on activities that bring about learning of standard science. The events described question this notion: Although I can find in the videotapes a considerable number of students who are genuinely interested in making sense of the phenomenon the teacher wants them to observe, so that “hands-on, minds-on” is an appropriate descriptor, they do not observe or understand the scientific phenomenon the teacher wants them to observe. From a phenomenological perspective, every interpretation emerges from the interaction of the horizon individuals bring to the situation and the horizon of the text and thing. In this interaction, world is divided into figure and ground. This figure brings out the aspects of the thing, the particular understanding of the text the individual looks at. Because students “put their minds on” to make sense of observations the order they perceive in most cases is not that of scientists. That is, in many situations students cannot perceive what they are to perceive because of their prior experiences and because the thing to be seen is not salient at all—but I return to these issues in greater depth in chapter 3.

Whereas the expression “hands-on, minds-on” suggests the interrelation of intellectual practices (“mind”) and the manipulable material world, it does not go far enough. Students’ conceptual objects that emerge from the intertwining of their lifeworlds, embodied practices, and social interactions frequently are not those of standard science. By itself, this outcome is not a problem: one can use such situations to engage students in exchanges where the different results would be discussed, critiqued, and researched. The phenomenon might arise as a (social) construction of the class. Problems arise when teaching is conceived of as the transmission of ideas. Students will feel rebuked when they evolve observation categoricals that the teacher does not expect. They may then begin to refrain from contributing at all. The videotapes exhibit that Christina is the only student to cite an experiment that disproves the teacher’s theory. But again, Toby does not capitalize on the situation but says that the events observed are due to unevenness of the table or the objects themselves without even investigating whether his suggestions make sense in the context of the young woman’s investigation.

The presented events therefore provide empirical evidence in support of the claim that it is unlikely that students will rediscover scientific knowledge in laboratory work in the absence of guidance and deep theoretical understanding. Many experiments yield unanticipated results so that students tend to “discover” an “alternative” explanatory scheme. In the tension between assessment and discovery,
students consequently focus on what ought to happen and are preoccupied with right answers.

WEAK AND STRONG ORDERLINESS

In the empirical examples, students constitute phenomena through their discursive (interpretive) and material practices. Students construct order in laboratory activities through modification and repetition of actions, observation sentences, and tentative observation categoricals. In this, they face the challenges of ordering the world of their experience that are little different from those of scientists whose task it is to impose order on the apparent disorder. The orderliness of the phenomena literally is in the investigator’s hands, and this orderliness offers itself in elaborating details of attempts, repairs, and discards locally motivated and locally occasioned modifications of any material shape. I can identify at least one major difference between the activities of the students in this Australian classroom and those that scientists enact. I may speak of a strong orderliness produced by the activities of scientists. This strong orderliness lies in the scientists’ practices to make their actions and therefore the phenomena they construe, accountable in ways that the students are not yet familiar with. The latter have little experience in repeating particular sets of actions such as to reproduce an outcome, making it difficult at times to produce a phenomenon in the first place and to produce accounts that withstand critique or are powerful enough to question other accounts. They lack the quality of agency that brings material manipulations and observation categoricals onto such a convergent path that sufficiently stable interpretations emerge. Students’ interpretations need to remain open in a classroom because what they think they observe may in many cases have to be revised as the artifact of their material actions and interpretations. So unless they are to experience failure or if they do not seem to mind running the risk of “being wrong” (like Christina for whom this is a part of learning), they avoid making firm commitments in the form of phenomena they constructed on their own.

One can therefore speak of weak orderliness produced by students. Their phenomena and the associated accounts are subject to revision and deconstruction. In many instances, the final judgment about students’ phenomena has been made by the teacher; in others, he decides that “data that disproves a theory” generated by students are artifacts. Here, the orderliness students produce easily can be destroyed and renounced. However, this weak orderliness can also change into strong orderliness when positively evaluated by the teacher’s comments; then, the orderliness becomes detached from students’ actions and something that belongs in the realm of scientific objects and events. Students’ orderly phenomena become ratiﬁed and thereby reiﬁed as phenomena.

AGENCY IN SCIENCE LABORATORY

In my ethnographic research of scientists at work, I can see how their actions and the facts and explanations they produce become irremediably fused; it is only
through rhetorical efforts and the linguistic dissociation between objects and scientific agent that scientific objects become independent. The present episodes show that the orderliness students produce—especially when, from a scientific point of view, they are artifacts such as Jon, Rhonda, and Sean’s observation categorical “sliding objects move with a constant velocity”—and their actions are inseparable. For the purposes at hand and until further notice, tentative observation categoricals form the basis for future observations (often in the form of confirmatory bias) or tests. Actions and objects are discursively separated when students are certain that the resulting events are reproducible, subject only to insignificant variation. (I show in chapters 6 and 7 how the split between material world making a sign and the sense it signifies comes about.) However, when it eventually turns out that a phenomenon should be considered artefactual—Sean and his mates who deconstruct their phenomenon, Christina who abandons her phenomenon that contradicts the teacher’s theory because he said so—the interdependence of action and phenomenon is reintroduced. For, one of the ways a phenomenon can be deconstructed is through a declaration that the preparation was artefactual.

My descriptions retain this unity of action and objects: any description, observation sentence, and observation categorical always is an outcome of, and visibly connected to, some prior action or action sequence. Furthermore, models and implicit hypotheses (and theories) that integrate mental and material objects are made explicit. By also indexing actions to singular individuals, my descriptions show how worldly objects, embodied practices, and social structure come to be intertwined to form the world of students’ experience. This approach to representing human agency allows me to eschew the reductionism of other approaches that only focus on mental or physical actions, social or technological dimensions of laboratory work, and content or contexts; it is a symmetric anthropology that integrates all these dichotomies. This approach is thus appropriate for analysts who view knowledgeable as emerging from the interaction of the task, the individual, and the (physical, social, and cultural) setting; and it is appropriate for analyses that recognize (a) the heterogeneity of actions, goals, motives and activity and (b) the seamless way learning arises from situated activity.

The sample events show that the phenomena students produce emerge from the intertwining of discursive and practical activity, interactions with others and the material world that is the focus of their tasks. Seen thus, it is not surprising that students’ phenomena often do not correspond to those the teacher wants them to perceive and explain; furthermore, students cannot even assess which of their actions do not conform to the teacher’s instructions because to do so they already need to perceive the phenomenon with scientific eyes and know the theory from a scientific perspective. These results have considerable implications for science instruction through laboratory activities. To see what a teacher wants students to see and to do what the teacher wants students to do, students already need to know what they are supposed to learn. My microanalyses cannot be directly translated to provide recommendations for appropriate actions. To escape from this dilemma one needs to look at the context in which laboratory tasks are situated. In the present videotapes, the teacher simply labels those results “wrong” that do not fit into
his explanations and there is evidence in the data sources that some students felt ridiculed by his remarks in these situations.

Toby has missed many opportunities that can facilitate student learning and he does not capitalize on the possibilities that arise from students’ constructions of different phenomena. He tells students what they should observe or talk about the legitimized description (in terms of equations) of the system of objects they observe. On the other hand, he may ask students to argue the different outcomes of their activities, make their material and interpretive activities accountable, test alternative outcomes and explanations, and work on consensual explanations. By not engaging with students to discuss their observations, he too misses opportunities for learning. By listening to students and by engaging with them in a truly symmetric conversation, he can learn much about students’ knowledge, their way of perceiving the objects and events of the laboratory, and so on. By discussing any differences in their observations, students are provided with the opportunity to experience an important aspect of science: the temporally emergent construction of phenomena (facts, objects, events) that arises from the interaction of individuals with material, social, and cultural worlds. By reflecting on their own constructive processes and products as the result of such interactions, they may come to understand standard scientific facts and explanation as outcomes of similar situated processes; and they have opportunities to wrestle with the question, “How does science manage to get facts out of the messiness, the confusion, the hunches, the subjective judgments, the broken test tube, the leaps of faith that are inherent in the experiment?”

An appropriate approach may begin with the assumption that the phenomena and observations students produce are diverse, different from, and incompatible with, legitimated and legitimate views. Rather than suppressing these phenomena (and with them the students who constructed them) teachers need to establish forums in which this diversity can be discussed and contrasted with standard views (which the teacher may need to contribute). In this way, teachers may answer the question, “Could you design hands-on experiments that raise doubts about the conclusions that were historically drawn from them instead of experiments or demonstrations that make the conclusion seem obvious or inevitable?” However, details of how this is to be done and how students learn under these new and different conditions are still open questions to be addressed by future research.

Another consequence of the present observations is that the capacity of traditional laboratory tests to do what they are designed to do has to be questioned. In the physics classroom under investigation, the teacher provides students with an instruction sheet intended to guide them through an investigation during which they collected data that were to be interpreted. These interpretations are the products used as evidence for an evaluation. However, such a practice is questionable when students have no indication of what their investigation is to yield. In this case, they have no means to assess whether their individual steps are situationally appropriate to collect those data needed to get to the answer that the teacher normatively established as the reference against which to judge students' answers. As an alternative, one might imagine that students choose their own problem to which
they seek a solution. The evaluation might then assess the degree to which stu-
dents’ processes and products are convincing. As part of their efforts, students may
establish a portfolio that documents their efforts including videos and written arti-
facts. Of course, students themselves also need to be asked about the degree that
they think they achieved their initial goals. Again, future research needs to evaluate
the suitability of such an approach for assessing students’ laboratory competence.