Authentic Science Revisited

In Praise of Diversity, Heterogeneity, Hybridity

Wolff-Michael Roth, Michiel van Eijck, Giuliano Reis and Pei-Ling Hsu
Authentic Science Revisited
NEW DIRECTIONS IN MATHEMATICS AND SCIENCE EDUCATION
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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 The series aims at becoming a leader in providing refreshing and bold new work—rather than out-of-date reproductions of past states of the art—shaping both fields more than reproducing them, thereby closing the traditional gap that exists between journal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.
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In Praise of Diversity, Heterogeneity, Hybridity

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Over a decade ago, *Authentic School Science* (Roth 1995) focused science educators on a different way of thinking about learning and teaching science. The book-length report was the result of a three-year effort at one private school for bringing about change in science curriculum, teaching, and learning. The ideas underlying the school-based effort derived from the emergent literatures on practice-based epistemologies and the social studies of science with their reports of how the laboratory sciences construct their objects. But the ideas were also grounded in the participant teachers’ own training, which had led most of them through the master’s level and even into doctoral studies.

Over the years, we have begun to revisit and rethink what the term “authentic” might mean, in part as a result of our reading and own research on knowing and learning science in the everyday world outside schools, including—but not limited to—our studies among scientists (laboratory, field), technicians of various kinds (water, fish hatchery, electricians), and public (environmental) educators. In this regard, an important aspect of knowing and learning in the everyday world is the free choice people have to engage in this or that form of activity. Eventually, we have come to know cultural-historical activity theory, which has changed our way of thinking about knowing and learning. For this reason, our own efforts in designing science curriculum have changed so that we now emphasize, to the extent that this is possible, students’ participation in the very practices for which school is supposed to ready them. Therefore, some of the examples featured in the present book are environmentalists’ data collection episodes in local marine environments, high school students’ internships in university science laboratories, and middle school students’ participation in environmentalism.

Made possible by several grants from the Social Sciences and Humanities Research Council of Canada and the Natural Sciences and Engineering Research Council of Canada (all to Wolff-Michael Roth), we came together in the same location at about the same time to do research in different sites but with overlapping interests, concerns, topics, and even collaborative research. Our laboratory (Cultural and Historical Approaches to Thinking [known as either CHAT@UVic or CHAT lab]) provided the physical space for meetings, which included not only ourselves but also other individuals working from the same framework even though on different topics. Our interactions with these other members of the CHAT lab were helpful in developing our ideas. We are also thankful to our participants, such as the scientists in the water laboratory, to the different (groups of) environmentalists, and to the teachers and students participating in the various studies that we report here. We thank Diego Ardenghi, Nadely Boyd, Leanna Boyer, Cathy Carolsfeld, Gholamreza Emad, SungWon Hwang, Bruno Jayme, Mijung Kim,
PREFACE

Yew Jin Lee, Misty MacDuffy, Asit Mazumder, Lilian Pozzer-Ardenghi, Lenny Ross, Judith Sales, Angus Stewart, Ian Stith, and Nikki Wright for the feedback, support, and interest that they provided and showed to our work.

Some of the chapters draw on materials that were part of journal articles we had written and published in the context of our research program focusing on different forms of scientific literacy for those with interests in science careers and those who do not have such interests. Chapter 1 arose from a plenary talk Wolff-Michael Roth presented at the international workshop “Guided Construction of Knowledge in Classrooms” at the Hebrew University, Jerusalem. Chapter 2 is based on an article first published in the *Journal of Science Education and Technology*. Chapter 5 further elaborates and contextualizes a study originally published in the *Journal of Research in Science Teaching*, whereas parts of earlier forms of chapter 6 have been published in *Science Education*. In chapter 9, we draw on and extend materials that initially appeared in *Enseñanza de las Ciencias*. We thank the publishers for the opportunity to re-use the materials as part of the copyright transfer agreements. We have freely drawn on the materials and have changed them to suit the need for coherence in the present book.

Research such as the one reported here and the books in which they result would not be possible without the support of those closest to us, our families, who generally exhibit tremendous patience when we, researchers and scholars, get buried in what we do. Our thanks go to Sylvie Boutonné, Irene Koster, Hanna van Eijck, Jesse van Eijck, Juliana Reis, Ana-Julia Reis, Maria-Luiza Reis, and Wen-Chun Ting.

Victoria, Canada
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INTRODUCTION

BRIEF HISTORY OF “AUTHENTIC SCIENCE”

In the 1980s, a diverse literature from quite different perspectives and disciplines was brought to convergence in the discipline of education generally and in science education more specifically. These literatures included, on the one hand, the work on knowing and learning in everyday out-of-school situations epitomized in the work Jean Lave had done among Liberian tailors and among grocery shoppers in California, Sylvia Scribner’s studies of mathematics in dairy factories, and Ed Hutchins research on navigation among Puluwat Islanders and on navy vessels. On the other hand, there was an emergent literature on science and how it was really done rather than how it appeared in the methods narratives of published research. Karin Knorr-Cetina, Bruno Latour and Steve Woolgar, and Michael Lynch all conducted laboratory studies that subsequently influenced generations of researchers and their thinking about what it means to know and learn. Practice theory and the social studies of science were born as domains of inquiry.

All of this research pointed toward the need to rethink what it means to know and learn, which came to be phenomena that were to be explained in terms of the observable social practices in which participants and members engaged rather than in terms of grey matter between the ears and the structures in peoples’ minds—which are forever inaccessible in and during interactions with others. Especially Jean Lave’s work evidenced the difference in the practices people enacted and thereby exhibited when working on school-type tasks (e.g., paper-and-pencil mathematics tests) and on everyday tasks, such as shopping and making “best buys.” Educational researchers began to think that the school-like practices, though practices in their own right, had little to do with what was required in the everyday world. And yet, schools were believed to prepare students for this everyday world. The upshot of this research and the related theoretical advances was a recognition that what students did in schools, and therefore what they learned in such environments, bore little relevance to the requirements of the everyday world outside them. This recognition was the origin of the concept of authentic knowing and learning.

In the context described, the adjective “authentic” was meant to denote what people were doing in their everyday pursuits outside schools. That is, whatever we called authentic was not to be associated with getting a passing mark on a test or the rote memorization of facts beyond students’ reality. Thus, a mathematician develops and proves theorems, a historian analyzes historical texts, a scientist designs and implements experiments. These patterned actions characterize the work in these professions. In the late 1980s and early 1990s, calls emerged for schools to teach in ways so that students would be put into situations where what they do has some (family) resemblance with what the mathematician, historian, or scientist
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does as part of her or his daily work, and the idea of developing “authentic” curriculum meant creating such opportunities. But how would one move from the lecture style situations or recipe-style school science investigations to curricula that allowed “authentic science” to emerge in schools? This is where the original curriculum development and research reported in *Authentic School Science* took its origin.

In the summer of 1990, Wolff-Michael Roth had read all the major ethnographies of science and all the major works on mathematics in the everyday world. As a department head of science, he encouraged and then implemented with most of his teaching staff at Appleby College “open inquiry,” that is, a context in which students designed their own experiments, which they then conducted, and the results of which they reported and defended to their classmates. In many instances, the students in physical science (tenth grade) and physics (eleventh and twelfth grade) not only designed their own investigations, but also the materials and equipment (instrumentation) needed to conduct the experiment. For example, the students who had decided to study wind friction on cars built cardboard models of different shape or size and tested wind friction using these models and an existing low-friction airtrack. Other students working on a joint chemistry-physics project built their own gas chromatograph from a variety of materials that they found around the schools, their home, or which they bought in nearby stores. We extended the work into eighth grade, where students conducted their own research in and on ecozones and ecotopes. Later, we continued this work by designing curriculum for even younger students, whereby fourth-grade students learned about forces and stability by designing and building three-dimensional architectural structures (towers, bridges, tent-size structures) or where sixth- and seventh-grade students learned Newtonian mechanics and simple machines while designing and building prototypes of hand-driven devices.

In all of this work, we found that there never was a problem with motivation. Students lost themselves in the projects of their own design and, at all stages, lost track of time, always astonished that their scheduled class time was up when the bell rang. But what we could not change in this type of curriculum was the ultimate focus of all school-related tasks: the production of artifacts that had no other goal than receiving grades in exchange, which, in contrast to knowledge in and of the world outside school, constitutes the real currency that students use and exchange for access to other opportunities after school, including access to universities, colleges, and jobs.

Over time, therefore, and especially since the mid-1990s, we became dissatisfied with a key aspect of our “authentic science” concept: the students were still confined by the school- or government-set curriculum. What they produced ended up in written reports on paper and in oral reports to their peers, but the products never made it outside the classroom—even though at the elementary level, they would feature at exhibitions during special community and parent nights. Our thinking then was concerned with the possibility of designing curriculum where what children and students produced was actually useful to their community more generally. These ideas initially were articulated in an article provocingly entitled
“Deinstitutionalizing School Science.” The term was inspired by the movement in psychiatry to move patients out of hospitals and into the community, where they would be supported in the attempt to integrate them back into their local community life. The halfway houses of the penal system are based on a similar idea, where, after doing their time in prison, individuals are provided with the opportunity to reintegrate into the community by living in these special places that provide some constraints over “normal life” but fewer constraints than “prison life.”

The first curriculum based on these emergent ideas led us to make connections between school science and environmentalism that already happened in one community on the Canadian West Coast (see chapter 9). The curriculum was explicitly designed to foster the open exchanges between schools and other parts of the community where they were located. The following section describes where we were in our thinking around the turn of the century. It foreshadows everything that we would subsequently do and that shaped the work reported in this book.

RECONFIGURING AUTHENTIC SCIENCE BY FOCUSING ON LEARNING IN HETEROGENEOUS AND OVERLAPPING KNOWLEDGE-BUILDING COMMUNITIES

In the late 1990s, we were ready to change our focus as to the meaning of “authentic,” believing that we needed to move out of the school and allow students to “take up” the motive of ongoing activities in their community, such as gardening or environmentalism. One of us wrote a proposal that allowed us to move into new directions both theoretically and practically, by actually teaching what we were “preaching.” The intent of the study we proposed to our funding council was to develop theories for learning (and teaching) in one community (Brentwood Bay) where different groups engage in activities related to the same focal point. In Brentwood Bay, the Hagan Creek watershed at the time (or in the near future) was the focus of activity for different groups including Bayside Middle School, Stelly’s Senior Secondary, the Hagan Creek Environmental Project (headed by the UVic EcoLaw Chair), Central Saanich Water Advisory Council, local farmers, a First Nations’ Band, and a group of local residents with interest in providing trout spawning habitat. Documenting how the interaction of all groups with interests and stakes leads to learning and changes in their understanding requires a multi-site ethnography that simultaneously documents the activities (including knowledge and beliefs) within the different groups. In the past, research studies had taken small windows on learning. We understood that such narrow views provided limited understanding of knowing and learning in a community, let alone in multiple interacting and heterogeneous communities. Studies had looked at teacher learning or student learning. And in each case, the studies not only overlooked the relation between the two, but also the learning of members as they interacted with others (e.g., researchers and parents). Our purpose was to pursue research that would address these inadequacies. Initially, our core site would be Bayside Middle School where we had piloted innovative science lessons in which students studied Hagan Creek and made their results publicly available to the community during an open-house event and on an Internet web page. We were particularly interested in how
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knowing and learning would arise from the interaction people have with the artifacts, representational technologies, tools (including instruments for data collection and computers), and individuals from various communities, including scientists, First Nations people, elderly, parents, students at different age levels (high school, elementary school), and businesses. These studies will be based on partnership relations involving members of the various communities.

Traditionally, educators associated scientific literacy with scientists’ science. The basic metaphor for teaching was information transfer, book learning, and bland and routine laboratory activities. The past 30 years of science education research showed that this led to largely unsuccessful attempts in getting students to understand, appreciate, and get interested in science and scientific careers. More recently, constructivism was the main alternative referent for planning and enacting science curriculum. However, even with a focus on students’ understanding, little had changed in the actual practice of teaching and the focus was still on scientists’ science. Simultaneously, science curricula focused on individualistic aspects of learning rather than competent participation in science-related activities in the communities where students lived.

In contrast, our own recent research in classrooms showed that curricula focusing on the development of the discourse at the level of the school classroom bring about much more change at the individual level. Furthermore, our research showed that if students are in charge of identifying the focus and purpose of their science activities, motivation and therefore learning are tremendously higher than in regular classrooms. Whereas this past research and the curricular implementations based on it were successful, it was always within school walls, where teaching and learning occur isolated (disconnected) from the local community. That is, our curricular interventions were successful but failed to provide learning contexts that integrated learning into the community at large, thereby decreasing the impact of all other current efforts. We therefore began to argue that activities that took students out of the classroom and into the community, engaged in legitimate peripheral participation in science-related activities, such as ecological assessment of local watersheds, were excellent ways to foster learning of authentic science practices. We argued that science education has to get out of the classroom and become relevant in everyday life because science affects students daily, their parents and the community as a whole. We thought that this type of experience would increase the interactions of school with society and therefore increase learning opportunities, provide a motivational component (the students learning is for the betterment of the community) and, in the end, improve the learning of individual students. We argued that the learning that takes place in such an endeavor is not restricted to students. We noted and intended to demonstrate that all participants in such an enterprise learn.

At the time we were planning the curriculum innovation and associated research, there was a substantial project underway performing environmental analysis and attempting the restoration of Hagan Creek, a local creek in the Brentwood Bay (British Columbia) area with historical and biological significance. This project—called Hagan Creek–Kennes, the western and aboriginal names of the
HAGAN CREEK:

Wolff-Michael Roth cotaught lessons with resident teachers and preservice teachers. We invited scientists and environmentalists to work with the children while they collected data at Hagan Creek. A water technician from a local farm also assisted students to collect biotic and abiotic information at various sites along the creek. Parents, including those from the local First Nations Band, accompanied students, teachers, and scientists. During the lesson following a two-hour data collection, the teacher and Michael (and sometimes a scientist and environmentalist) helped students to find pattern in the information on the speed, width and depth of the creek, and different microorganisms living at the site of each student group’s research. There also were six students from another seventh-grade class who recently completed similar units who assisted their peers in getting started with doing research in the creek. Students used the microscopes, beakers, ice cube trays, eyedroppers and other equipment, plus graphing paper, which we prepared together with the teacher. Michael also taught data analysis lessons during the mathematics classes, drawing on five computers installed in the classroom that ran statistical software. Ultimately, the teachers and the research team assisted students in constructing classical public displays and Internet websites to report their research results to the local and global communities.

In this description of one type of activities in the proposed project, one can see how members of different parts of the Brentwood Bay community—parents, environmental activists, scientists, teachers, preservice teachers, students—moved in and out of their respective sub-communities (Figure 1.1). Each time there was some contact, we saw learning events where knowledge from one community was transferred to another. Thus, even if a member of one community interacted with another and therefore, in some sense, was a legitimate peripheral participant, it was possible to document learning. For example, the preservice teacher learned tremendously about science, teaching, and learning in communities as she worked and interacted with Michael (Roth), an experienced scientist and science teacher. The Hagan Creek–Kennes project scientists and environmental activists also learned from the data collected by the students and about the impact science education can have on the community; they also learned about the challenges of teaching and about how get young people interested in the issues that would concern them later in their lives. Parents and other members of Brentwood Bay learned about Hagan Creek from the children, and the First Nations children (normally attending
their own tribal school) learned from the experiences of the Bayside Middle School students through Michael’s teaching. Furthermore, by following these individuals in their own communities, learning occurred as people interacted with each other.

As a result, we proposed to our national research council to concurrently investigate learning by working with an interdisciplinary team of three doctoral students and one post-doctoral fellow to research all sites described above. This research is described, in part, in chapter 9. We intended to pull these strands together so that we could construct images of learning that took into account all four sites simultaneously. The interest of so many different parts of the Brentwood community in the Hagan Creek watershed offered unique opportunities for studying knowing and learning and the resulting change as it occurred when multiple stakeholder groups interacted. We were in the unique position of researching these changes in situ rather than having to rely on (limited) historical records of the change in communities.

This project potentially had a tremendous impact not only on science education in school, but also on science education as it pertained to the community at large such as Brentwood Bay. Interacting with members of various sub-communities allowed people to become aware of different forms of knowledge, knowledge-generating processes, and concerns that are different from traditional science but have valuable contributions to make to understanding ecological relationships (e.g., Traditional Ecological Knowledge). Documenting, understanding, and theo-
rizing simultaneous learning in multiple overlapping but heterogeneous communities was the topic of our research. We learned a lot about science in and for the community, not as a set of facts and process skills to be memorized, but as a means to be mobilized by people in the contest over the environment and contested resources (e.g., access to the water grid) and as a contested terrain, when the sciences and their procedures were interrogated and where scientists disagreed with respect to exactly what the facts were that pertained to the issues at hand.

AUTHENTICITY AND KNOWLEDGE BOUNDARIES: BETWEEN FORMAL EDUCATION AND WORKPLACE

In the course of this work, our ideas about what “authentic” might mean have changed. We increasingly became aware of the boundaries that appeared to exist between different forms of activities, where what counts as knowledgeability in one domain does not count as such in another. Thus, school science knowledge is in almost all cases irrelevant to the issues debated in the public domain. For example, few if any one needs a definition of Newton’s laws or the second law of thermodynamics or the Krebs cycle to go about their daily businesses. But people do need to know about chemical and biological contaminants of their wells, how the contaminants change over time and with the seasons in order to increase their chances of survival. It became clear that lifelong learning was more important than the acquisition of an arbitrarily selected body of scientific facts, concepts, and theories for the purpose of making it to the next grade level or into college.

Lifelong learning is a *sine qua non* for successful transition into modern knowledge-based economies. Thus, the Commission of European Communities holds that “lifelong learning is no longer just one aspect of education and training; it must become the guiding principle for provision and participation across the full continuum of learning contexts.” Knowledge-based economies will change much more rapidly than traditional economies because of the exponential increase in total knowledge; individuals will be required to continuously update their knowledge to keep pace with the increasing demands of our globalized society. An International Labor Office report suggested that if knowing and learning are not renewed, adaptation to new environments by individuals, and therefore by communities or nations, would be reduced and even become impossible, thus leading to exclusion and eradication. Arguably the most critical points in any lifelong learning path occur when learners leave formal education to enter the world of work. It is at this juncture that many people experience numerous gaps between their “book knowledge” and what is required in the “real world,” meaning the world outside school (which in fact constitutes the real world in which students live and survive for 12 years or more). As people must adapt to changes in the workplace, they often attend learning institutions to gain the skills that they are expected to bring back to the job. How does their job experience mediate learning in the formal education setting? Little was and still is known about how individuals navigate the boundaries between their “book” and “real-world” knowledge and between “real-world” and book knowledge. Knowing how people navigate this
boundary is of tremendous importance to nations like Canada, which are embracing a knowledge-based economy. “Updating” and “retooling” are increasingly required to maintain skills at marketable levels. Understanding how people manage to move back and forth across knowledge boundaries requires appropriate empirical studies and theory (which will be discussed in the course of the present book).

Common lore holds that knowledge is something people carry around with them wherever they go. Knowledge is supposed to be context free, applied anywhere independently of the particulars of a setting. Yet situated-cognition and social-practice research has shown for years that everyday human knowing varies considerably with context. It varies so much that the amount of mathematics individuals studied in high school correlates little with their competence on mathematical tasks in the workplace. Our own research among scientists shows that they, too, fail to provide correct answers to graphing tasks culled from introductory university courses of their own field. Simultaneously, whatever the everyday situation, individuals turn out to be highly competent in the mathematical demands at work and other everyday situation. These findings suggest that competence is related to an individual’s activity within a specific community, and less to transportable knowledge that is “in their head.” Yet schools supposedly prepare students for life after school, at work and in other everyday situations. If the problems people experience in the transition lies with the school, it may need to change the ways in which it prepares citizens for productive lives in today’s knowledge-based economies. If, on the other hand, the problem lies in process of crossing the boundaries between formal education and after-school experience, we need to better understand what it involves for at least two reasons. First, in an increasingly fluid labor market, people may have to return to formal school contexts to “upgrade” or “retool.” If what they know is of little use in the formal educational setting, then learning, which is a function of what people already know, is seriously handicapped. Second, for recent graduates and for returnees, the relevance of what they learn to the context after school is of primary importance to secure employment.

These and similar ideas led us to propose studying individuals who repeatedly move across knowledge boundaries, from formal education to work and from work to school, somehow perhaps adapting knowledge from one domain for use in another. Specifically, our project consisted of intensive ethnographic case studies that detailed the movement of individuals and groups between different systems of activity: formal education and out-of-school situations (work). Because of the expertise developed in prior research, we concentrated on situations in which scientific and mathematical tools (visual representations, instruments) are used. Pilot projects show that typical participants are college students who also work or do summer jobs, students in co-op programs, individuals in (e.g., electrician) apprenticeship programs, or high school students in work-study or career preparation programs. A central outcome of our project would be a grounded theory conceptualizing the boundary crossing activity. A more rigorous understanding of the requirements of successful boundary crossing between formal education and workplace has practical outcomes in that they allow educators and administrators to design more effective programs and transitions into the workplace. Extensive prior interdisciplinary
research and publications in education, cognitive science, sociology of science, and applied linguistics (see research contributions) prepared Wolff-Michael Roth to lead a research team through the challenges and to take advantage of the opportunities that such an endeavor offers.

**AUTHENTIC SCIENTIFIC LITERACY: AN ATTEMPT AT “SCIENCE FOR ALL STUDENTS”**

The research project described in the previous paragraph led to the work that Giuliano Reis did as part of his doctoral dissertation, and it set us up for writing another grant that brought the two other authors, Michiel van Eijck and Pei-Ling Hsu to Victoria to work on elaborating what “authentic” might mean in the context of science and scientific literacy. In that grant, which led to the founding of a center for scientific literacy, we focused on a double-pronged approach, where interested students could pursue internships in laboratories and also had opportunities to engage with science as it was practiced at the community level—for example, in the form of environmentalism or where it existed in the form of traditional ecological knowledge.

We began with the supposition that science education reforms in Canada parallel those that occur internationally in their attempt to promote scientific literacy for all students: All students of race, gender, cultural heritage or socioeconomic status should be able participate in the ongoing public debates about issues in science, technology, and society and environment (STSE) salient in a technology-oriented global economy. But this does not mean that everyone needs to know science in the way scientists do. Rather, we had come to realize that it means that students develop knowledgeability to engage others with very different forms of knowledge over contested issues in the community. The anticipated knowledgeability for all students to participate in public debates needs to reflect standards that are achievable by a wide range of people and that reflect a high degree of relevance enticing many citizens to actively participate in issues that concern an increasingly complex society. Whereas for our science education colleagues this generally meant to engage in more direct teaching, telling students what they needed to know, we pursued different avenues.

There are at least two types of scientific literacy required in modern society. First, an increasing part of the population wants and ought to participate in STSE-related decision-making processes without having to study science at the university. In other words, they are not scientists. Second, the steadily expanding scientific and technological knowledge requires experts who can bring special and specialized expertise into the decision-making forums. A central unifying theme of the center for the study of scientific literacy was the exploration and documentation of both forms of scientific literacy: One general, attainable by all, and one geared to prepare those pursuing scientific and technological careers to become experts in a related field. The context for many activities will be, as further described below, pressing issues that concern not only Canadians but also people of other industrialized and non-industrialized nations—the environment, water, and weather.
INTRODUCTION

The part of the ultimately funded center that we (the authors) realized was designed to provide authentic science experiences to students. The notion of authentic experiences in school was created after research had shown—mostly with respect to mathematics—that much of what people do in their everyday lives is unaffected by their school experiences. The fundamental idea emerging at the time was that literacy (knowledge) has to be understood in terms of practices—the patterned actions people deploy in their private and working lives—rather than as procedural and declarative information stored in their heads that they bring to bear on simulated problematic situations. Thus, we proposed that students of mathematics, science, or history engage in activities that bear considerable family resemblance with the activities in which scientists, mathematicians, or historians normally are engaged in. Here, knowledge was thought to be equivalent to competent participation in these activities, and learning is recognizable as changing (increasing) competence. Authentic School Science (Roth 1995), one of the very first studies in middle and high schools, showed that there was tremendous potential in having students learn science by designing and conducting their own research programs. Despite the tremendous success of the Authentic School Science program, as described above, there emerged doubts not only for ourselves but for the science education community whether the things scientists do in their labs provide the appropriate image for the education of all students. In particular, the competitiveness within the sciences is said to reproduce unequal levels of access for women, the poor, and those of culturally different origins (African American, First Nations). We thought of participation in any form of activity where science is also brought to bear on decision-making, as long as this activity is the real thing rather than a mock-up, appears to be a better image for providing meaningful science experiences to the student population at large. Thus, some of the suggested activities include participation in environmentalism, salmon enhancement, ethnobotany for economic survival of aboriginal communities, and active citizenry.

In our node of the center—there were two other nodes focusing on different aspects of scientific literacy, like teacher education—we took a two-pronged approach in providing authentic experiences in the two ways defined above. On the one hand, we provided authentic science for diverse student populations (and their teachers), with particular attention to the needs of students from First Nations, to become scientifically literate to the extent that it prepares them for participating in public debates, community decision-making, and personal living consistent with long-term environmentally sustainable forms of life. This aspect was designed to increase the scientific literacy of students on a broad scale. On the other hand, we provided opportunities for a small, interested, and select group of students and teachers with internships in scientific laboratory and field research, particularly targeting students from First Nations. This aspect of our work was designed to increase the number of students eventually interested in pursuing scientific and engineering careers. Various research groups and individual scientists would support both aspects of our node in providing relevant activities through an Outreach program. There were three main projects that we developed.
First, the project *Water, Environment, and Public Health* provided internships for interested high school students and teachers, focusing on the areas of environmental and engineering approaches to sustainable water quality. Internships included trips to watersheds used for drinking water, associated treatment and disinfection of water, scientific understanding of physical, chemical and biological factors affecting water quality and health safety. Laboratory internships involved focus on state-of-the-art analytical and modeling tools used to characterize, quantify, and model water quality patterns and their relationship to environmental quality under variable climate scenarios. In chapters 5 and 6, we report one some of the things we learned about science learning as we followed a group of students from their high school biology classroom into the lab.

Second, the project *Seaquaria in Schools* was underway in twelve public schools throughout BC. It uses chilled seawater aquaria housing local marine ecosystems as a focal tool for environmental education. As students cared for and monitored the health of their Seaquarium, the living creatures create a lasting emotional tie and concern for the health of their local environment. Teachers were regularly consulted to incorporate their experience, expertise and ideas into a hands-on approach to the delivery of an integrated curriculum. This included solidifying the links between classroom learning and experiential outreach programs such as those coordinated by SeaChange Marine Conservation Society. Whereas this approach addressed many prescribed learning outcomes and many of the Department of Fisheries and Ocean’s marine conservation and stewardship mandates, it also helped create opportunities for the transfer of learning to meaningful local and global stewardship initiatives (e.g. participating in community development plans and Ocean’s Day events). Mentoring and public displays offer occasions for young people to develop their communication and leadership skills, and finally the program offers food for the hearts, minds and spirits of all students as they are continuously exposed to exceptional cultural, physical and intellectual learning opportunities.

Third, the *EcoRowing* project focused on marine education, conservation and restoration. It works with other environmental educators to provide watershed based experiential and classroom activities to schoolchildren (K–6) within the Capital Regional District (i.e., greater Victoria area). The program involved discussion of the natural history and First Nation’s values for exploring the environment; study of the marine environment on the dock, measurements of pH, dissolved oxygen, temperature, turbidity and salinity to assess water quality, and samples collection of plankton for further study in the “lab” area with microscopes; wetlands explorations from a First Nations perspective: traditional ecological knowledge is used to explore this environment, as first peoples may have had to do; and participation in a community celebration such as Ocean’s Day, where displays help to educate the public about the actions and concerns of the schools. In chapters 3 and 4, we describe some of the things we learned about science learning while we followed elementary students into the outdoor settings.

The SeaChange Marine Conservation Society and the university science laboratory described above also constituted the contexts in which we came to follow and
work with aboriginal peoples, one of whom is centrally featured in chapter 8 on his journey from between the two contexts. The first of these contexts focused on the traditional ecological knowledge of the local aboriginal peoples, whereas the second one emphasized modern Western scientific ways of understanding the surrounding world.

All these experiences, once brought together, contributed to redefine the meaning of authenticity in science education some 12 years after one of us (Roth) first approached the idea. In the present book, we now represent the backbone of our rethinking of what authentic science looks like.
PART A

APORIAS OF LEARNING SCIENCE
In this first part of our book, we reflect on some of the problematic issues arising from thinking about science learning. The problems we articulate may not have a solution, which is why we included the concept of *aporia* in the title of this part. An aporia is a perplexing difficulty, most frequently without a resolution or answer. However, the very fact these problems are brought to light creates room for change to take place.

In this book, we conceive of authenticity in terms of the etymological origins of the term in Greek, where it was associated with original authority, a person doing things himself, and a master. But we also put the term in a semantic field where it lies close to author and authorship, creation, the production of things. In this part, we show that there are some fundamental problems in the constructivist idea of knowledge building, because all construction and building has to have an object/motive, which, as *intentional object*, orients what a human subject or agent does. To construct knowledge, the learner would have to know what it is to construct, that is, the learner has to know the knowledge or at least would have to have something like the building plan available to the architect. But to the learner, the knowledge (concepts) to be learned constitute *terra incognita* so that he or she cannot know what to do in a landscape unknown to them. Could Christopher Columbus predict what he would be doing once setting his foot ashore? No! He did not even know about what today are called the Americas.

In chapter 1, we deal with one of the essential paradoxes of learning: students are supposed to focus on learning something that they do not yet know. The question is, how can they intend to learn something if the something orienting their search is available only after they have learned it? The German critical psychologist Klaus Holzkamp, who had taken up the cultural-historical activity theoretic analyses that Alexei Nikolayevich Leont’ev had outlined, especially the agenda concerning the requirement for a science of the subject, did not think it was possible for administrators to plan learning ahead of time. He called the idea of administrators being able to plan learning a fiction. In this first chapter we outline some of the points that allow us to question the idea about learning as being directed from the outside of the learning subject. This then sets us up for articulating a form of authentic learning, which we understand to be learning as seen from the point of view of the subject of learning. Anything this learner does has some grounds, which provide reasons for doing what he or she does. It is only when we know these grounds that we can truly understand what learners do and why they are doing it, even and especially if they are doing things very different from what the teacher planned for them to do. Ultimately, therefore, we doubt that the very idea
of planned “learning pathways,” which some of our European colleagues have developed, makes any sense whatsoever.

The issue of the grounds of our actions is important and very little attended to. Human beings act in ways that are intelligible and reasonable to them, and which, as we work out in chapter 7, they can assume are reasonable and intelligible to other people as well. Now, if students talk about natural phenomena in certain ways that science educators call “laden with misconceptions,” they do so because language already provided them with resources and reasons to talk in this way. In our work, therefore, we do not intend to eradicate ways of talking students bring to schools. Rather, we intend to provide opportunities where they can extend their current ways and develop new ways of talking about natural phenomena. When individuals recognize that engaging in something because they will be able to expand their action possibilities, they will do so and in a very motivated way. The learning that occurs in the process is expansive learning, which contrasts defensive learning that most students engage in during their school time directed toward avoiding negative consequences, such as low grades, punishment, suspension, and so on.

In chapter 2, we focus on the role that information-technology-based research tools can play in rethinking “authentic” school science. Given the central place IT-based research tools take in scientific research, the marginal role such tools currently play in science curricula is dissatisfying from the perspective of making students scientifically literate. To appropriately frame the role of IT-based research tools in science curricula, we propose a framework that is developed to understand the use of tools in human activity, namely cultural-historical activity theory (CHAT). Accordingly, IT-based research tools constitute central moments of scientific research activity and neither can be seen apart from its objectives, nor can it be considered apart from the cultural-historical determined forms of activity (praxis) in which human subjects participate. Based on empirical data involving students participating in research activity, we point out how an appropriate account of IT-based research tools involves subjects’ use of tools with respect to the objectives of research activity and the contribution to the praxis of research. We propose to reconceptualize the role of IT-based research tools as contributing to scientific literacy if students apply these tools with respect to the objectives of the research activity and contribute to praxis of research by evaluating and modifying the application of these tools. We conclude this chapter by sketching the educational implications of this reconceptualized role of IT-based research tools.
CHAPTER 1

ACTIVITY, (LEARNING) OBJECTS, AND INTENTIONALITY

On “The Fiction of School Learning as Something that can be Planned”

In the early 1990s, the German critical psychologist Klaus Holzkamp—who, having developed and further elaborated Alexei N. Leont’ev’s cultural-historical activity theory, considerably influenced Jean Lave with respect to her thinking about learning—gave two subsequently published presentations in which he interrogates the relationship between teaching and learning. He points out that official school curricula, teachers’ (often required) lesson plans, and prescribed learning outcomes all point to an underlying deterministic model according to which teaching brings about learning irrespective of any intentions students might have. Holzkamp (a) questions the possibility of school learning as something that could be planned and (b) suggests that teaching possibly interferes with learning. We would short-circuit our analyses of classroom events when we assume that the teaching of a curriculum (concepts) and learning (curriculum contents, concepts) are equal according to the formula “students learn what teachers teach.” As we personally know from many years of teaching science, everyday teacher talk exhibits this equivalence. Thus, teachers (and professors, too) assume that because they “have covered” some topic, students also know it. But we consider Holzkamp to have raised legitimate concerns especially with respect to the nature the match between the objects/motives of schooling and curriculum, on the one hand, and students’ goals, one the other. Thus, we need to know whether students have appropriated in their goals the collective motives for doing what they do or whether the collective motives are inverted and undercut in the students’ goals for the activity—as this was the case of the working class that Paul Willis (1977) observed in his Learning to Labor. The disparity between the two occurs even under the assumption that schooling in fact is interested in learning (e.g., science concepts) rather than, as the French philosopher Michel Foucault suggested, a way of hierarchically structuring student population and access to job—and income-related opportunities. In this chapter, we do not intend to reproduce Holzkamp’s argument but rather, after sketching his argument, we make the provisional assumption that students indeed want to learn what the curriculum prescribes. We show that even under this condition, there are irremediable contradictions whereby students cannot see, for example, precisely those phenomena that support the concepts they are to learn; and we show that the inner contradiction of organized learning that arises from the fact that the learning object intended by the system inherently is unknown to the students, who therefore cannot reproduce the motive of activity in their own goals (intentions).
CHAPTER 1

Drawing on an activity-theoretic formulation of the object-oriented nature of human activity forms and a phenomenological formulation of perception, we highlight (by drawing on empirical case materials) the inner contradictions in present-day cognitive theories that presuppose learning as intentional (e.g., present in all forms of constructivism) but fail to theorize the essential passivity involved in learning. Fundamentally, any activity requires an intended object, but in teaching-learning situations, the intended object is precisely what lies outside the purview of the learner; how can students learn something (i.e., engage with the object of learning) that inherently cannot be intended? After articulating the various aporia concerning intention, objects of activity, and learning, we provide an empirical case of guided inquiry, which highlights both the inner contradictions in any teaching-learning situation and the (fundamentally restricted) possibilities for reaching planned learning goals at all.

LEARNING: A CULTURAL-HISTORICAL ACTIVITY THEORETICAL PERSPECTIVE

The Nature of Human Activity: The Activity | Action | Operation Dialectic

To understand learning from a cultural-historical activity theoretical perspective (Leont’ev 1978), educators and learning scientists first need to understand that the term activity does not denote what students do in classrooms, which, in the root language of activity theory (German), would be Aktivität (activity in the sense of being busy doing something). Tätigkeit (dyatel’nost’), however denotes a formation that contributes to the production and reproduction of society. Thus, farming, fishing, raising cattle, or manufacturing cars all are activities in the sense of activity theory. Doing a word problem in school does not constitute an activity. The second major often-overlooked point is the dialectical nature of activity: It is the unit of analysis and all of its identifiable structures are but moments that mutually constitute each other. A moment is an identifiable structure within activity that cannot be thought independently—though it can be identified perceptually and cognitively. In other words, we cannot talk about any structural aspect (moment) of activity independent of all other moments. For example, in an analysis of the activity system of farming, we cannot think of the subject—e.g., farmer, laborer—independent of the object (food production, income), outcomes (spelt, oats), means (tractor, seeds), the division of labor (owner, worker, tractor driver, seed operator), the operative rules (defining the relations between people, for operating tools), and the community that ultimately consumes the food produced (Figure 1.1). The point is to look at what happens, and this always will involve all the moments that we articulate here. We do not think about activity in the abstract or by assembling it from separate elements but rather we think about activity as a unit that cannot be further reduced and thought as a composite of independent elements.

The special point cultural-historical activity theory makes over other theories is that this entire unit as depicted is the minimal or smallest unit (element). Because activity is the smallest unit, it makes no sense to speak of the knowledge of the
subject independent of the activity system as a whole, including the intentions (goals), envisioned outcomes, the means, and so forth. It makes no sense to speak about the object independent of the means, as we know that a Canadian grain farmer with heavy equipment who hires ten combined harvester thinks and acts very differently from the Mali millet farmer attempting to grow enough grain to get his family through the year. As we show below, using this same kind of analysis in the context of schooling radically changes how we can think about learning and what we can expect students to achieve (on a theoretical basis).

In activity theory, the activity has a collective motive, which, at the most general level, is the survival of society and, with it, the survival of the individual subjects, who take up the collective motive into their personal goals. For example, neither Canadian grain nor the Mali millet farmers have to worry about clothing, for they can exchange some of their grain or earning for clothing; similarly, the tailors do not have to worry about producing or gathering food, for they exchange the clothes they make for food. Each member of society, by contributing with something useful collectively to society as a whole can, in whichever way this may be, contribute to his/her own individual survival. Besides, in meeting their needs (housing, clothing, food) through the exchange of goods and services, individuals also expand control over their life conditions. More so, the division of labor within society actually gives members the freedom to choose in which way they want to contribute, allowing them to match their personal goals with collective motives.

Activities are rather large units and describe at a general level the ways in which society has evolved to meet primarily the basic needs of its members and secondarily the needs that emerged when increased control of the environment has freed up time to be spent in leisure. These activities are realized in different ways in the individual empirical cases that we may want to study. Thus, farming can be studied empirically on any one of the farms in industrialized countries, the private (square-meter-sized) plots people may own even under the most restrictive regimes (e.g., in the USSR and China, much of the fresh food has been produced on plots smaller than the front yards of North American homes), or in village economies in Africa or Asia. However, individual farmers, whatever the size of operation, do not think about activities; they do not orient themselves toward society as such. Rather, they
orient toward specific goals, which are realized in and through their actions (Figure 1.2). These goals, however, stand in a mutually constitutive relation with the motive of activity, because a farmer decides to till and then tills the field using a hoe or tractor in order to prepare the planting of seeds; but farming only exists in a concrete way because there are people farming and meeting their basic needs by exchanging (part of) their harvest against other basic needs.

In relation to school science, students act in certain ways because they realize schooling rather than some other form of activity. Our actions are oriented toward (mediated by) the goals we attempt to achieve; goals and actions are never only mine (i.e., someone’s property), but are inherently shared with others who participate in and constitute the activity at hand. We do what we do to realize the activity at hand; and others precisely understand what we do because it realizes the activity, which gives what we do its sense (in a different activity, what we do has a different sense). The activity constitutes the ground and the reason for an action; that is, this ground is common such that our actions are immediately intelligible. In other words, the relation between the two levels (activity and action) is one of sense (Figure 1.2): thus, “ideality is at the hinge of the connection between me and others” (Merleau-Ponty 2002, p. 24, original emphasis).

The action level is the interesting part for analysts, as humans generally engage in learning-oriented behavior when they realize that this behavior increases their action possibility, their room to maneuver, and therefore their control over the current problem specifically and their situation more generally. Human subjects engage in learning loops, that is, when in doing something that does not immediately contribute to productive activity and production, they recognize that they can expand their agential room to maneuver. In this situation, therefore, the expansion of concrete action possibilities available to the subject not only constitutes learning but also greater control over its life conditions. This form of learning therefore is
both expansive—i.e., greater control—and associated with positive emotional valence—it is better to have greater than lesser control/power over our life conditions.

The actions that realize the goals are composed of unconscious operations that respond to the current conditions (Figure 1.2). Thus, for example, the Canadian farmer who has decided to till using his tractor does not have to think about shifting gears because all the different movements required to shift unfold occasioned by the current state; he may give instructions to his farm worker without choosing words and thinking about how to seriate them to produce a grammatically correct sentence. These operations and the actions they realize therefore stand in a mutually constitutive relation: operations realize actions, but (the current state of) actions orient and condition operations. The action serves as referent for the operations that realize it (Figure 1.2). However, as the example of shifting gears shows (an example that Leont’ev also used in paradigmatic way), operations, which can be raised to consciousness and unpacked into further operations, have to be thought as crystallized actions so that operations inherently are cultural-historical formations. Together, the collective sense, which ties the action to societal (collective) activity, and embodied reference, which ties an action to the operations that realize it, stand in a mutually constitutive relation that we denote by the term meaning. In a strong sense, therefore, meaning cannot be made; it always already exists in a double dialectic that is shot through by culture enacted in and through active participation in activities and available in the operations (which constitute sedimented and crystallized cultural practices [patterned actions]).

Schooling and Learning

In much of educational thinking and practice, there are hidden inner contradictions that become evident when schooling is framed in terms of cultural-historical activity theory. Thus, especially as evident in accountability schemes, teachers are thought to constitute the subject whose actions (“teaching”) are oriented toward students, who, by means of the curriculum, are transformed in the process by increasing their knowledge (Figure 1.3a). The figure shows how students are thought of as the object of teachers’ actions. A typical prescribed learning outcome in the British Columbia Biology 11 outcome illustrates how students come to be objectified in this approach: “By the end of this course, students will have an understanding of the structures and function of the male and female reproductive systems” (Biology 11 and 12 Integrated Resource Package 2006, p. 73). The document also specifies that “schools have the responsibility to ensure that all prescribed learning outcomes in this curriculum are met” (p. 17). (Not surprising, the curriculum document uses Bloom’s behaviorist taxonomy to characterize domains of learning.) In this configuration, students are not decision-making subjects but the target of teacher actions that are intended (have the goal) to transform them. Not being the subject, the student has no stakes in realizing some motive through specifying their own goals.
The first conceptualization of students is associated with a second one, in a sense contradictory to the first (Figure 1.3b). Here, students are seen to be the acting subjects who engage with the curriculum (self-motivated, other-motivated) to produce (i.e., construct) knowledge. The inner contradiction is immediately salient: whereas the vision of the outcome is part of the cultural-historical activity-theoretic framing, students precisely cannot realize the object/motive—they do not know the knowledge they are to produce and therefore cannot intend it. As a consequence, they cannot assess whether what they see, hear, do, or know is what they are supposed to see, hear, do, or know. This inner contradiction neither is diminished nor disappears with guided or direct instruction, as here, too, students do not know what they are asked to do or why they are to engage in the curriculum although they are familiar with the negative social consequences of failure (punishment). They have no way of assessing whether what they learn—whatever it is—increases their agential room to maneuver and control over life conditions. A second contradiction is the fact that although constructivist educators emphasize the active engagement of learners they nevertheless set the learning goals thereby again putting students in a situation where they have to achieve externally set goals that they inherently cannot know. Because students are not free to choose the activity system or the goals, they do not know which motive they realize or why they are asked to
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achieve externally set goals. That is, the motivation has to be supplied from the outside—punishment, grades, and threats of suspension and expulsion from school are different means to bring any unruly students in line with the goals of the teacher.

A very different situation exists when students and teachers collaborate on something that inherently makes sense because it already is a societally motivated configuration that students may or may not yet know about but which exists as real and relevant activity. In one curriculum innovation project, more extensively described in chapter 9, one of us cotaught seventh-grade students in a unit on water and environment (Figure 1.3c). Rather than prescribing what students are to do (and learn), we asked them to choose how they wanted to respond to a call for action in an environmental activist group in a local newspaper. Although the object was in part the same for all student groups that formed, they concretely realized their participation in environmentalism in very different ways; and correspondingly, they set the goals for what they wanted to do and how they wanted to do it. These students, therefore, essentially were in control of choosing the particular form of participation in environmentalism, the object/goals, and the means that mediate the achievement of them. For example, a group of boys decided to measure the speed of the main creek at various locations and to correlate it with the frequency of different microorganisms. A group of girls, on the other hand, decided to record the pollution of the creek in various places in the form of a news feature, shooting photos, recording impressions on tape, and interviewing local politicians. There were as many different forms of contributing to environmentalism as there were student groups. Because these students were in control over the object and the means of realizing it, they sought and engaged in learning opportunities whenever they felt the need to expand their action possibilities and levels of control over their project. In the end, they reported their findings to the community during an open-house event organized by the environmentalists in the village; the results of students’ findings and work also were featured in the local newspaper and on the website of the environmentalists.

In this curriculum unit, learning occurred, but what students learned no longer was under the control of the teachers. Students defined what they had to do to increase their own agential room to maneuver to achieve the goals that they had set for themselves. For example, one group of boys wanted to know whether different parts of the creek provided different habitat for the resident trout. In talking to a biologist, they found out that the oxygen level of the water is a key factor determining the suitability of a location as habitat. The boys then solicited the help of a biologist we knew and asked to come with us into the field. This biologist then taught them the use of a dissolved-oxygen meter (Figure 1.4), which allowed the students to pursue their project of measuring the suitability of different reaches as trout habitat. In pursuit of their goal, determination of trout-bearing habitat, these students engaged in a learning loop precisely because it expanded their action possibilities. Because learning was directed toward the expansion of their control and room to maneuver, it was inherently motivated; and once achieved, the outcomes, associated with positive emotional valence, had further motivating effects on stu-
dents. In any event, because they framed what they wanted to do that they could not yet do, students identified and identified with the learning object.

This brief analysis also should make apparent that most analyses of school learning do not take into account the cultural-historical aspects of the activity in which students find themselves: schooling. Thus, most learning scientists deal with problems at the individual or classroom level, leaving out the cultural-historical dimensions of schooling and the way that societal structures mediate what happens in schools, what is being taught, how it is taught, and so forth. Because of such omissions, it is virtually impossible to understand the differences in achievement between students attending, for example, U.S. metropolitan inner-city schools, on the one hand, and those attending schools in the same metropolitan area but located in the suburbs, on the other hand. In the course of our experimental unit, we came to realize that we had to analyze the learning of the students in this experimental unit on science and the environment in terms of the cultural-historical development of the village community, its climate and the water woes associated with it, and the environmentalist movement, the analysis of learning generally. This, if we wanted to be consistent with a cultural-historical approach, required us to include schooling as the proper minimal unit for the analysis of learning. We realized that is only when we understood the extent to which students took up the motive of activity in their own goals that we could establish the level to which specific learning behavior can be understood.

LEARNING AND INTENTION: A PHENOMENOLOGICAL PERSPECTIVE

There is a second major theoretical framework that allows us to make thematic several important contradictions in the construct of learning generally and the con-
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This theoretical framework is concerned with the role of intention in perception and learning, highlighting that intention does not exist as such but always has an object—intention is transitive, binding subject and object into an irreducible unit. Thus, “[e]very thought is interested (not uninterested), i.e., an elucidation of a Vorhaben ‘prepossession’” which motivates—that must equal in evidence” (Merleau-Ponty 2002, p. 17). Similarly, the verb to construct is transitive. In learning theories, the object is knowledge. Students are said to be engaged in the construction of knowledge. In the previous section, we point out that activity and actions are oriented toward (collective) motives and (individual) goals, respectively. In other words, they are intentional, though at different organizational levels (individual, society). Intentions, too, are central to a phenomenological perspective on perception generally and on learning, specifically. The interesting aspect about institutionalized learning setting is the inner contradiction that students are supposed to learn what they inherently cannot intent, because they do not know what they are to construct (the particular knowledge) and therefore cannot have it as a goal that orients their actions; and they do not know the means they can draw on and what the raw materials are that they can use. More so, the very perception that is needed to isolate the raw materials (part of the object of activity) required in knowledge construction precisely requires the knowledge that is to be learned. This inner contradiction is captured in the following incompossible condition:

1. To see in a teacher demonstration the phenomenon that subsequently supports a scientific concept, students need to know the concept (theory-laden nature of perception); and
2. To understand a scientific concept requires students to see it in operation in relevant phenomena.

Although demonstrations and laboratory experiences are premised by the idea that students would see phenomena on which the scientific principles to be learned are grounded and which they explain, the highly problematic nature of this premise became clear to us during a study of learning in an Australian twelfth-grade physics course. The study had several components concerned with what students see in their hands-on investigations and lectures. Pertaining to the latter, we had set up an experiment whereby students, near the end of a six-week study of rotational motion, were presented with the set up of an investigation similar to one that they had already observed. The demonstration-investigation involved a person sitting on a rotating stool spinning a bicycle wheel (Figure 1.5) and holding it in two positions: the axle of the bicycle wheel is (a) parallel to the axis of the stool and (b) perpendicular to the axis of the stool. Students were asked to note their predictions prior to observing the teacher-investigator performing the demonstration-investigation, and finally to explain what they have seen.

The result relevant here pertains to the second case, where the axle of the spinning bicycle wheel was perpendicular (at right angles with) the axis of the stool. Whereas 18 students observed motion of the person around the stool axis, five observed no motion. Some of the students who observed motion later referred to a
similar investigation—where the bicycle wheel is hung from a string attached to the ceiling and to one of its two handles—and explained with the physical concept of precession. The five students who did not observe motion argued that the two relevant axes were perpendicular to each other so that there could not be any motion. In this instance, students were already alerted to observe an event, and some aspects of the event of course immediately are salient such as the teacher’s hand/arm motion to get the bicycle wheel to spin. However, the key feature of our study is that students observe mutually excluding facts—there is motion versus there is no motion.

In this study we also show that students face a similar contradiction when they conduct designed investigations where they are to observe certain phenomena that the teacher subsequently uses as a basis for introducing and explaining theory. The inner contradiction can be articulated in the following incompossible pair of simultaneously correct statements:

1. To know that what I observe constitutes what I am supposed to observe, I need to know that what I have done is precisely what I was supposed to do; and
2. To know that what I have done is what I was supposed to do, I need to know that what I see is precisely what I was supposed to see.

Because students do not know what to look for before knowing the phenomenon, but need to look in order to know, it is impossible for them to intend learning specific knowledge. That is, as learners we are passive with respect to the contents of our future learning: at any one moment we cannot know what only a few minutes later we might have learned. We are radically passive with respect to the knowledge we acquire. As learners, we are not in the situation of a child who is engaged

Figure 1.5. The physics teacher conducts a demonstration asking students to write down what they have observed.
in finding the hidden person in an image—the child knows she is looking for a person; and as learners, we are not in the situation of masons, who know what the houses they construct from the bricks in the yard will look like. Rather, as learners we are in the dark about what it is that we will eventually know, and we are in the dark about what teachers want us to know until the moment we know both the knowledge object and why teachers have instructed in their particular ways (Roth 2006). But of course, as learners we bring to the situation the traces past experiences have left in our bodies, which is the light that co-exists with the dark: as learners we therefore are both in the light and in the dark about what it is that we are to learn and know.

These considerations lead us to a more encompassing incompossible pair of statements concerning learning:

1. To intend to learn something, I already need to know the something; and
2. To know a something, I (first) need to learn the something.

In other words, to intentionally construct knowledge, this knowledge is a prerequisite to guide our intention to learn; but if we already know this knowledge, we no longer need to intend “constructing” it. That is, it is impossible to intend learning what one does not already know in the same way that it was impossible for Christopher Columbus to have intended the discovery of the Americas. In a strong sense, therefore, this means that we are passive with respect to the learning that occurs to us—we can only acknowledge (etymologically derived from cnâwan, to recognize [know again]) that we have learned something once we already know it.

GUIDED LEARNING: AN EMPIRICAL EXAMPLE

In the previous two sections, we articulate the inner contradictions in planning instruction and in learning from experience. When instructional goals are set—whether in behaviorist, cognitivist, or constructivist fashion—students are little more than cogs in and of a machinery designed to change them. Whether students actually become knowledgeable is irrelevant as long as they achieve (or showcase) what the teacher intended. Furthermore, even when students are in situations where they are asked to observe or engage in some task in other ways, it is inherently impossible for them to intend learning a specific form (content) of knowledge, because if they knew what they are supposed to learn, they did not have to intend learning it. But precisely because of the inner contradictions (paradox) in learning, there is the possibility for grounding and supporting arguments for guided learning. As a result of a teacher–student transaction, analyzed in this section with close attention to the details of the setting, the students come to see what they had not seen before while running a computer simulation of simple Newtonian motion of an object on which a force acts. This case study provides a context for chapters 3 and 5 that deal with the different ways in which teachers and old-timers engage elementary and high school students with quite varied outcomes.
ETHNOGRAPHIC CONTEXT

Here we briefly report on a naturalistic study designed to investigate knowing and learning in a real classroom setting where students, among many other forms of engagement, also used a computer simulation tool—Interactive Physics—to learn about Newtonian motion so that they could, at the end, design learning tasks for younger students. In three sections of an advanced physics course for twelfth graders, groups of students were videotaped while completing a series of tasks that began with explorations of forces on the motion of objects to the design of a game for younger students.

Setting and participants The study was conducted in a private, British-style college-preparatory, co-ed school in Canada. The students generally were from well-to-do families, though students from lower income families attended, too, having received general or sports scholarships. The achievement levels were comparable to the local public schools. The students (N = 47) were enrolled in an advance-level physics course focusing on qualitative understandings of concepts. The course was designed following principles of social constructivism. For the purpose of this chapter, we focus on the interaction of one group of students, involving two males (Glen, Ryan) and one female (Elizabeth). They are typical of the school population in that they all aspire to go—and since have gone—to college, though, as the predominant number of students, not into the sciences, opting instead for more lucrative careers in business and law.

Task environment Interactive Physics is a computer-based Newtonian microworld that allows users to conduct motion-related experiments. Observables such as force, velocity or acceleration can be made visible as vectors or represented via instruments such as strip chart recorders and digital and analog meters. All student activities in the present chapter included, at a minimum, one circular object (Figure 1.6). A force (full arrow) could be attached to this object by highlighting and moving it with the mouse. The object’s velocity could be modified by the students and was always displayed as a vector (line arrow). Students were asked to find out more about the microworld, especially the meaning of the arrows. The denotations “«force»” and “«velocity»” are used here as convenient way to denote force and velocity vectors whatever the students’ current way of calling them.

Cognitive task analysis Physicists articulate the relationship between some net force (F)—which is the resultant of the forces in and opposing the direction of a moving object—acting on this object and its velocity (v) in the form of

$$v(t) = \frac{F}{m} t + v(t = 0)$$  \hspace{1cm} (1.1)

where m is the mass of the object, t the amount of time that the constant net force has acted upon the object, and v(t=0) the velocity at the moment that the force has
begun to act. The underbar denotes the vector nature of velocity and force, meaning that these quantities have both magnitude and direction. Thus, in considering the effect of the force on the present velocity, students have to take into account the relative directions of the two. If, for example, the direction of force is opposite to the direction of velocity then the speed (i.e., magnitude of velocity) of the object decreases; if the two variables point into the same direction then the speed of object (i.e., magnitude of velocity) will increase. In Interactive Physics, the vector nature of velocity and force is implemented by means of arrows, which have both magnitude and direction. In the situation depicted in Figure 1.6, the object would begin moving to the left but, accelerated by the upward pointing force, would increase its speed in upward direction until, in the limit, it would move in the same direction as the force.

**Data and analyses** Conversations of three student groups over and about the Interactive Physics tasks were recorded during four one-hour periods separated by two-week intervals yielding a total of 12 hours of videotapes. The video was digitized and completely transcribed, including pauses, overlaps, and images of relevant screen displays. Our method for analyzing the data was based on microsociological research on everyday work practices and human-machine interactions and conversational analysis. The nature of the tasks required students and teacher to talk about the screen displays, thereby producing natural protocols of sense-in-the-making.

**Coming to See**

In this section we exemplify how through teacher guidance students come to see phenomena that they have not perceived before although opportunities have existed for this to occur. It is in the course of episodes such as the one discussed below that students come to perceive new phenomena, setting them up to learn about how to theorize them in the way the standard sciences do. Thus, in the context of their tasks doing simulations in the Interactive Physics environment, it turns out
that many students do not provide observation descriptions of events suitable for understanding the theory that the events are said to provide evidence of. They cannot even know what they need to look for to get them onto the path that will allow them to understand the system.

Setting up the intervention  Up to the point of the episode in the transcript featured here, followed the spirit of the opening query, “What have you found out so far?” The session then takes a turn. So far the teacher—as his next discursive move exhibits—evidently has not gotten the sense that students have found out what the task had asked them to. He now sets up a configuration of «velocity» and «force» such that the former points straight up and the latter straight down. Inherently, there is no difference to any other configuration where the two arrows are set in opposite direction; however, this particular configuration, because it embodies an “up–down schema” grounded in the everyday experience of living in the gravitational field of the earth, provides the possibility of an analogy with throwing an object (such as a ball) into the air, which is then pulled to the earth by the gravitational force. Such analogies are foundational for relating new experiences to an already familiar world shot through with meaning. That is, new words, objects, and perceptual experiences accrue to meaning, allowing students (Elizabeth, Glen and Ryan) to further articulate how the world works.

Episode 1.1

50 T: see (2.48) WHAT if you had that point up? (2.93)
   (The teacher moves first «velocity» then «force» into the configura-
   tion shown: velocity straight up, force straight down.)

51 G: it would go straight down.
52 R: yea [it would go] downward.
53 T: <<p>[okay:      ]>
54 (1.04) ((Teacher runs the simulation, which results in
   the screen display depicted below.))

55 E: and i thi[nk=it went backwards ] first tho[ugh].
The teacher engages students. In and through this transaction, students come to describe the motion in a way consistent with the Newtonian theory that they are to learn as part of the tasks that they currently complete. The episode begins by shifting the teacher’s position so that he can reach and manipulate the mouse, and with it, the objects that appear in the microworld. As he rotates «force» to point downward and «velocity» in the opposite direction, he asks students a question of the type “What happens if . . .?” (turn 50), which potentially is a productive question because it invites students to think and spend extended amounts of time investigating. For a physicist or any other person knowing about the physics of motion, it is clear that the teacher reduced the complexity of the situation—much like a driving instructor who takes her students onto a parking lot—because students now only consider linear rather than curved motion. More so, the specific orientation chosen is up–down. What happen when this configuration is “run” does not depend on the up–down orientation—any orientation will do. But the up–down configuration of the arrows sets up the possibility of drawing a real-world analogy with throwing an object straight up into the air.

Glen immediately suggests that the circular object will go straight down, and Ryan nods and expresses agreement (turns 52, 53). This apparently reifies what may have incited the teacher to begin this demonstration in the first place, for, from a physicist’s perspective, the answer is not correct; because of the initial velocity pointing upward, the object should move into that direction prior to the reversal of the velocity due to the force (see task analysis). Because the students have been working with this particular simulation for nearly 15 minutes, it is likely that it has mediated what they learned so far.

Simulating an event The teacher’s “okay” (turn 53), may confirm having heard students’ hypotheses about how the object would move, but, uttered with little speech intensity, he may have been talking to himself as if confirming his hypothesis about students’ current understanding. Without a response, we cannot know what the effect is of the utterance, and therefore we cannot know the speech act itself. In the pause that follows, the teacher “runs” the simulation he has prepared (turn 54), yielding an event in the microworld as shown in the offprints (turn 54).

We do not know what is in the teacher’s head and therefore what drives his moves, that is, why he does what he does. But the students do not know this either. All they can go by is what the teacher makes available to them. Because the ana-
lysts can see the teacher moving the object, there is the possibility that students, too, see significance in his action for whatever (hidden) reason. The very fact that the teacher does engage with them may be a resource for understanding that what they have said as inappropriate. But then, the episode is unfolding so quickly that nobody really has the time to stop and think; rather, the teacher has set up this intervention within seconds and then engages students in a question–answer sequence that does not contain the frequently observed evaluation component typical in what researchers have come to denote as the initiation–response–evaluation (IRE) pattern (see more on this in subsequent chapters).

Generating alternative observation descriptions With the traces of the object positions over time displayed on the monitor—this feature of Interactive Physics works like time-lapse photography—three individuals speak at the same time (turns 55–57). This is not unusual for everyday conversations especially when there has been a pause, which is a feature that goes away only when someone speaks. The longer the pause, the more there is a social obligation (at least in Western societies) to speak—the standard maximum being of the order of one second. Elizabeth notes for everyone to hear that the object has first moved upward before engaging the downward motion that Glen and Ryan previously predicted. The teacher begins but immediately stops again at about the same time that Ryan—simultaneously with Elizabeth—describes the motion as having been “upwards.”

We can almost hear (and certainly in the transcript see) Elizabeth’s surprise and change in orientation. She begins her utterance and in the middle of the word “think,” her speech intensity (volume) increases, thereby hearably drawing the attention of others to something that she has seen and that therefore can be seen generally. It is an object available for general observation because “[apperceiving of the object qua object] is in general the first universal typification—precisely the [typification of the object] as an object of experience, an object of perception, and the [typification of unities] as a configuration of objects” (Husserl 1945, p. 335, our translation, original brackets). Elizabeth stresses both the words “went” and “back,” and then adds the temporal adverb “first” and the conjunctive “though.” We now unpack this part of the interaction. The particle “though” is both conjunctive and an adversative particle that expresses a relation between two opposed facts or circumstances in which one of the facts is inadequate but both do occur. The utterance of “though” thereby renders the earlier descriptions (the object as moving down) as matters of fact—rather than as hypotheses in the way they have been proffered before the simulation. That is, although Ryan and Glen have made their statements prior to the simulation, their utterances now have become observation sentences. But Elizabeth’s contribution constrains the applicability of the two earlier utterances, which now have become observation sentences. How? In and by means of her turn, Elizabeth provides an improved observation: “it went backwards first.” That is, because “though” has conjunctive function, the current state of affairs is this: First it [object] went backwards and then it goes downward/straight down. This state of affairs is actually stabilized by events that have occurred simultaneously—Ryan also proffers an observation description, “it went
upwards” (turn 56). That is, following the slow-motion presentation of the simulation, the students generate alternative observation descriptions; and it is these descriptions that open up new possibilities for understanding and explaining the events on the computer monitor. It is important here to note that initially, students describe the object as going straight down; and they do so irrespective of what might have happened on their retinas, which is, given what we know about the computer display, first an upward motion followed by a downward motion.

**Confirmatory power of uncertainty** Uncertainty plays an important role in learning, though most of our readers may assume that uncertainty should be removed. But, although uncertainty in conversations generally creates further uncertainty, it can also be a resource for confirmation. (For more on the role of uncertainty in teacher questioning see chapter 3.) Here, Ryan prefaces his observation description by the modifier of uncertainty, “I think.” It is a statement typically found very early in scientific discoveries, constituting a rhetorical move that allows for the possibility to be incorrect because of one or another contingency not yet apparent to the researcher. That is, the “I think” modifies an observation as a possibility without requiring the speaker’s commitment so that he or she can easily renegue. Modifiers are used in the first stage in the social construction of scientific facts. In the present episode, the confirmation and stabilization actually occur simultaneously and for everyone to hear—it is mediated by Elizabeth’s utterance, which articulates a compatible observation sentence precisely then when “backwards” and “upwards” are heard as denoting identical states of affairs.

Our analysis appears to indicate that the issue has been settled. However—certainly because of the rate at which real time events unfold and the time it takes for human being to become aware of what has happened—the issue about the correct observation description remains open as the subsequent turns at talk show.

Overlapping the very end of Elizabeth’s talk, the teacher utters several, even unfinished but seemingly disconnected words (turns 57, 59). The first sound “th-” terminates in a sudden stop; the second is heard as “but” with a rising inflection generally attributed to questions; then there is a pause, followed by a repetition of the “first” that Elizabeth has finished uttering precisely 1.09 seconds before—though, again, with rising inflection. The particle “but” is a conjunctive marking that some statement is to be delimited, a fact has not been considered, or an exception. Here it is uttered with rising inflection as in a question that asks students to consider something the nature of which is not evident from the talk so far. There is a 0.40-second pause, and then the teacher repeats the temporal adverb “first?” with rising inflection (turn 59). These rising inflections allow the words to be heard as elliptic forms of the question, “But what has happened first?” That is, in this case the teacher asks the question to which Elizabeth and Ryan have already provided the answer. This raises two issues.

First, the appearance of this question at precisely this point is not surprising when we consider that even experienced Tetris players would require more than 1.2 seconds to become conscious of an object on the screen and to reflect on the next move. Here, the teacher’s utterance comes about faster than it would take for
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simple objects to be processed in mind. This speed has to be considered in the light of the fact that Tetris players are familiar with the objects that may appear, whereas the teacher is in an entirely novel, once-occurrent situation.

Second, the fact that the teacher raises an admittedly indeterminate question can be interpreted by other participants that something requires further talk, that is, that the answer provided so far still is insufficient to answer the larger question about what has happened in this simulation. Ryan rises to the task by immediately responding. He suggests that the initial velocity “would” go in the direction of the little arrow. It is not certain which arrow he signifies, because, as our analyses show, these students use the same term for both arrows and without apparently being aware of the fact that in any one situation, two speakers may use the same signifier to signify different arrows. In the present case, «force» is the shorter arrow whereas «velocity» is skinnier but longer. It therefore comes as no surprise that Elizabeth raises opposition in the form of a question, “didn’t it go backwards first?” Whatever Ryan has wanted to say, Elizabeth has heard it as an observation description that opposes her own. That is, whereas she has earlier described the object as moving “backwards,” her present statement exhibits that she understands Ryan to have reconfirmed his initial description according to which the object “goes downward.”

Ending uncertainty Before Elizabeth has ended, Ryan already articulates agreement with her (turn 62). They finish this episode with elliptical utterances but in apparent agreement, which, in effect, settles uncertainty at least for the moment. Following her conjunctive “and,” Elizabeth queries—as indicated by the rising pitch toward the end—whether they would “then get both arrows.” With the compound sentence produced by the conjunctive “and,” Elizabeth raises the question whether the object “goes backwards first and then get both arrows.” A possible hearing is that after having moved “backward first,” both arrows would point in the same direction because the object moves in the direction Ryan has indicated (i.e., downward). Ryan confirms, though with the qualifier “I think so,” and Elizabeth concludes with an affirmative “yea.” As the subsequent developments show, the teacher accepts what the students have formulated, as evidenced in his didactic move to allow students to link this phenomenon to some phenomenon in the real world. That is, although one can possibly read this transcript as not having settled the issues, the teacher, in going on, also declares it as settled, and therefore, as having satisfactorily answered his question.

Looking back over the episode, we note that initial observation statements—the legitimacy of which may have been grounded in students’ prior experiences with the software—come to be questioned after the teacher has run a particular simulation. The teacher’s move therefore mediates what becomes salient in students’ perceptions, and therefore, the objects that are available for their subsequent considerations and negotiations. Elizabeth and Ryan—in contrast to what the teacher has just said—raise the possibility that the object has moved upward prior to moving in the way the two male students said it would happen before the simulation was run. In the course of several utterances that raise an alternative observation description
as a possibility, at least two of the three students eventually make affirmative statements, which turn out to terminate the episode.

Salience and Sense

In this case study, we can observe students who, despite being instructed to find the relationship between the two arrows, on the one hand, and between the arrows and the motion of the circular object, on the other hand, do not know what to intend. They do not, as we show, know what to look for and, correspondingly, do not perceive an essential aspect of the trajectory of the object and the corresponding relationship between the velocity and force arrows (vectors) that constitute a conceptual layer superposed on the phenomenal layer (object, its motion). At this point they would be hard pressed if asked what it is they are to construct or, if indeed they construct anything at all. Every teacher will have heard students say that they are lost, which is a description that undermines that they are in an active construction process.

Unfamiliar learning environments, because of their inherently open structure, provide opportunities and constraints to learning. Thus, because on the monitor, the two layers are not distinguished and indistinguishable, there are both possibilities and constraints to learning, which derive from the co-existence of concepts and material objects in the same world. This essential relation between concepts and phenomena, though visible to the teacher who knows how motion and arrows should be, is not salient to the students and only becomes so through the teacher’s actions. This situation is not unlike that in which many learning scientists find themselves when transcribing videotapes recorded in noisy classrooms. There are moments where one can clearly hear that someone said something, and perhaps even how many words possibly have been uttered, without nevertheless being able to discern what has been said. Even after listening many times, we may not be able to discern the word until a moment when others or we hypothesize specific words that might have been uttered; at precisely that moment we clearly hear what has been said. That is, knowing what can be perceived and perceiving (or intending to perceive) are closely linked. This is also the difference between those students in the mentioned Australian study who see motion because they expect motion, and their peers who do not see motion, because they do not expect it to occur. Similarly, we had observed these Australian students during investigations with rolling objects, where they expected velocity to be constant and observed it to be constant velocity even though we, the researchers, clearly could see accelerated motion in all cases that the students look at.

In the present instance, the teacher intervened by setting up a special condition of the students’ investigation; and it is in that condition that the initial upward motion of the object becomes salient to the students. That is, salience for the students is the result of a special condition prepared by the teacher; and this special situation mediates salience. Thus, whereas we do not think that teachers can cause students to perceive specific objects and phenomena or learn specific knowledge, we
do think that the presence of the teacher and what he says and does constitute resources that mediate salience.

Educational researchers often claim that students “make (construct) meaning” or that they set up learning situations that allow students to make meaning. Such a framing is inconsistent with the analysis of everyday cognition that phenomenological philosophers have provided. Thus, from a phenomenological perspective, words do not have meaning but rather accrue to always already existing meaning. From a cultural-historical activity theoretic perspective, meaning is the relation between sense and reference that simultaneously ground our actions both in the ongoing collective activity and our embodied knowledgeability (Figure 1.2). Sense and meaning are not to be made but are relations; but these relations may be more or less salient. In and through communication, therefore, sense is marked and remarked, and thereby made salient. What a teacher says and does constitute constraints that mediate how students look and what they might perceive. This includes, as our research shows, prosodic markers by means of which changes in the situation or words can be made to stand out. Thus, by stressing (emphasizing) the contrastive conjunction “but,” the teacher not only marks that what has been said (“it goes down”) needs to be delimited but also calls attention to this delimitation. That is, in stressing the utterance of “but,” the teacher makes the contrastive conjunction stand out, increases its salience, and thereby explicitly calls attention to the need of delimiting earlier descriptions. (We are not saying that he has consciously done it as prosody generally is produced unconsciously.) More so, after a brief pause, the teacher also stresses the utterance of “first,” thereby marking that the aspect to be attended to appears prior to something described by the students or in the beginning of the trajectory. That is, the prosodically achieved emphasis operates at the auditory level in the same way that slow motion operates at the perceptual level; both are designed to make something stand out more than it does under ordinary circumstances.

Even if the teacher achieves certain aspects of language and of the perceptual display to stand out, he cannot determine what is salient to students. We do not know, for example, which percept corresponds to the “way the little arrow is” announced in Ryan’s utterance (turn 59). Teachers actually might find out at some later point that the students have used their utterances in ways that led them away from developing a scientific way of talking about phenomena rather than leading them towards more scientific expressions. That is, although teacher interventions provide resources for particular aspects of experiences and discourse to become salient, they do not guarantee that some intended entity becomes salient. Rather, each instant in a conversation constitutes possible bifurcation points where conversations go astray, that is, highlighting entities and processes in (by the teacher) unintended ways precisely because students bring their past experiences to the situation (embodied in their operations), which mediates what sense is salient at any one moment and therefore the meaning. This constitutes an essential observation that led us to our rethinking of science education generally and to the importance of revisiting the concept of authentic science in particular. To be experienced as authentic, learning environments have to allow students to articulate and iden-
tify expansions in their room to maneuver as seen and experienced by them rather than in some abstract curriculum objective that lies outside of what is intelligible to students. In the latter case, they do not see the motive for learning and therefore have no reason to engage with the learning object.

ADDRESSING THE LEARNING PARADOX

In this chapter, we articulate a cautionary approach to the idea of learning as a phenomena possible without intention; this allows us to ground the idea of guided instruction as long as we can assume that students reproduce in their goals the motive of the schooling activity system. This caution is meant to mediate any idea about the possibility of instruction to reach specific instructional goals that can be planned beforehand. On both cultural-historical activity theoretic and phenomenological grounds we suggest that students cannot intend the specific knowledge to be learned and therefore find themselves in a quandary. Teachers, though they may provide resources for certain discursive and perceptual features to stand out and be salient, cannot guarantee either sense or meaning, because the traces previous experiences left in students’ bodies mediate what they can perceive and learn at any one moment.

Here, at the end, we return to the statement Klaus Holzkamp made with respect to the fictional nature of the idea that school learning could be planned. Although we recognize the important role teachers play in mediating perception and the salience of particular discursive features, we concur with Holzkamp in the sense that we cannot ever assume that the students will learn and know what we intend them to learn and know, not in the least because learners themselves (including us researchers and teachers) cannot intend their future knowing and therefore their learning. The learning that we described in the second part of this chapter presupposes that students have appropriated the motive of schooling activity, or act in ways that are not incompatible at the surface to avoid being penalized or punished. Such a conclusion may also be derivable from a radical application of constructivist ideas—if prior experience mediates what and how someone constructs knowledge, we cannot ever determine what students will construct because we cannot ever know what it is that 20 or 30 students bring to class. The large number of students in regular classroom also mediates the amount of time a student can spend with any one student or with any smaller number of student groups that a class is divided into. Realistically, with 24 students divided into eight groups of three, a teacher will not have more than five minutes per group during a one-hour lesson; conversely, doing whole-class sessions, where a teacher is in a position to notice what is being said and done, cannot ascertain that most let alone all students stay on the instructional trajectory required to attain a pre-planed lesson objective. Here is where the warning is appropriate not to equate teaching with learning: more likely, what is taught is not what is learned in an authentic learning environment.

The upshot of these contradictions in perception and learning for our revisiting of the authentic school science is this. Whereas in the past we thought that science learning environments are authentic when students were asked to engage in in-
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quiry, we now think that students ought to participate in identifying which motives they want to choose for orienting their actions. Students ought to be able to identify what they need to learn to expand their possibilities in the pursuit of something that they really want to achieve. This brings us back to the very origin of the word authentic, which stems from the Greek *αὐθεντικός* (authentikos), first-hand authority, original authority, and someone who does things on his own and for himself. Authentic science, then, is science that students experience in and for themselves, of which they rather than others are the authorities, and which they mobilize for themselves (*αὐτό*). Here, control over conditions and determination of expanding the control are the primary identifiers of authenticity.
CHAPTER 2

INFORMATION-TECHNOLOGY-BASED RESEARCH TOOLS AND AUTHENTIC SCIENCE

Authentic science, information technology, and scientific literacy are intimately intertwined. Although not consensually defined, scientific literacy in some authentic form is currently a widely accepted objective of science education. It not only involves the knowledge of key concepts in the natural sciences, but also procedural understanding of scientific inquiry. Likewise, current scientific research is unthinkable without information technology (IT). In scientific fields like biology and geology, the use of IT as a research tool has completely and irreversibly changed the nature of scientific research. These changes are so radical that the scientists no longer need to know any of the “basic skills” that were common only a few years ago—e.g., how to do division using logarithmic tables. Consequently, to contribute to students’ authentic scientific literacy, science curricula should prepare students thoroughly in the use of IT-tools for scientific inquiry. Figure 2.1 from an ethnographic study that we conducted among scientists in a fish vision laboratory shows that both the image of a retina (left) and the signal of light absorption (right) are acquired by means of charge-coupled devices similar to the ones in electronic cameras and by means of computers. In fact, this method of doing research on the absorption of light in fish eyes was made possible by the innovative use of technology. In this case, whereas past research based on scanning the spectrum of light across each cell had to do with 400 data points, this research using CCD technology developed by the researcher collected more than 15,000 data points. Based on this research, the canon concerning absorption of light in fish retina was overturned, thereby leading to the significant enhancement of scientific knowledge.

Figure 2.1. Most scientific research today requires the use of information technology (IT), even in fields that may not have been associated to computers and technology such as biology. Thus, in one project, both the image of a retinal cell from fish eyes (left) and the light absorption spectrum in this cell (right) require IT to be produced.
From cultural-historical perspectives, IT is not merely a tool but, as all tools, integral to consciousness and cognition and therefore of any form of literacy—scientific literacy included.

Considering the aim of scientific literacy, the role of IT-based research tool in secondary science curricula is dissatisfying. Despite a steady increase in both the number of computers per student and the accessibility of particular IT-based research tools, like dataloggers and spreadsheets, ample research shows that the regular and effective use of IT-based research tools in science curricula is in fact rare. Analysis of international tests such as PISA even showed that achievement in scientific literacy is negatively related to some of the types of software commonly used in scientific research, like spreadsheets. In contrast to the transformation of the nature of science for professional scientists, IT-based research tools have yet to establish their transformative role in science curricula. This process is currently frustrated by specific guidance and support for curriculum developers in incorporating IT effectively in science curricula, that is, linked to pedagogy appropriate for the IT-tools at hand.

In this chapter, we articulate a way of rethinking the role of IT-based research tools in science curricula and use, to exemplify our ideas, empirical materials collected as part of Authentic School Science. We further build on the framework outlined in chapter 1, cultural-historical activity theory, which has been developed to understand the use of tools in human activity, namely cultural-historical activity theory (CHAT). Departing from this framework, we suggest that IT-based research tools, as other tools, are understood as constituting human activity, and, hence, neither can be seen apart from its object/motives, nor can it be properly understood outside the cultural-historically determined form of activity (praxis) in which subjects participate. Based on a case study of students participating in research activity, we point out how an appropriate account of IT-based research tools involves subjects’ use of tools with respect to (a) the object/motives of research activity and (b) the contribution to the praxis of research. We propose to reconceptualize the role of IT-based research tools as contributing to scientific literacy if students participate in research activity, that is, if (a) they control the application of these tools with respect to the objectives of the research activity and (b) contribute to praxis of research by evaluating and, eventually, modifying the application of these tools, also with respect to the objectives of the research activity. Both aspects aim at increasing the control students have over their learning environment and over the expansion of their own action possibilities and therefore, according to the definition provided in chapter 1, increase the levels of authenticity.

IMPORTANCE AND POSSIBILITIES OF IT IN SCIENCE EDUCATION

This chapter arises from a multidisciplinary research project, which attempts to answer the question how science education can contribute to the development of scientific literacy. Considering this aim, the role of IT-based research tools is a key issue because they are thought to have a transformative potential with respect to the aim of a science curriculum that contributes to students’ development of
“authentic” scientific literacy. Moreover, “authentic” scientific literacy involves the abilities, critical thinking, and habits of mind necessary for understanding a discipline. It also involves communicative competencies to inform or persuade others about scientific and technical matters, to participate in collective situations where science and scientific knowledge are mobilized for the solution of problems, and to take actions on related issues. This involves the competence to interpret highly symbolic, abstract and domain-specific figures that are the product of scientific research, including schematic drawings, graphs, tables, and so on. Research among professional scientists has shown that they rather understand such figures when they have detailed knowledge of the tools by which they were produced, like IT-based research tools for the acquisition, processing, and analysis of data.

For the present purposes, IT is understood as any given computer application. We focus primarily on computer applications that are used as tools in scientific research in the natural sciences. Although many specific research tools exist, virtually every IT application can be applied as a research tool. For example, to write a scientific paper, one needs a text editor, by which the text editor becomes a tool for the researcher. Thus, whether particular software application is a research tool is determined both by the context in which it is used and its inherent technological characteristics. In line with frameworks on the use of technology in social settings we understand IT in the human-shaped contexts in which it is used as a tool rather than only by its inherent technological characteristics.

Some IT applications are specifically designed as research tools, like dataloggers and modeling software. Particularly these IT-applications are said to have a transformative potential with respect to scientific literacy and their role is currently most significant in practical work in science education. To datalogging, for example, a number of attributes are assigned that should make practical work in the classroom more “authentic” or “real,” that is, more like a practice of scientific inquiry. It should improve the process of data collection, thereby serving potential gains in the types, authenticity, and quality of experimental data that students can access. It should enable students to repeat measurements and to vary instantly the experimental conditions with the need of the experimentation, which is widely recognized as a major improvement of datalogging as compared to traditional classroom measurements. Finally, datalogging is seen as an effective aid for exploring and interpreting graphical displays of empirical data and to support conversation about data and allowed students to evaluate critically the appearance of the graphic display. All these attributes should bring classroom science closer to “real” scientific inquiry. Indeed, attributes of IT as tools for inquiry contribute to high levels of experienced authenticity of a curriculum by creating opportunities for students to connect their daily life experiences with basic scientific or mathematical principles like heat and energy or change and variation.

Despite the overwhelming benefits of IT for inquiry-based learning, enthusiastic curriculum developers remained puzzled “why everyone isn’t doing it.” Even massive attempts initiated by governments to implement IT in the science classroom left the curriculum virtually unchanged. This is clearly observable in the UK, where datalogging equipment is most widespread in science classrooms (every
science section has datalogging equipment) and where the government has spent already £1.8 billion since 1997. Nevertheless, the educational inspectorate in England found that an appropriate and effective classroom use of IT is in fact rare. Based on findings like these, one may conclude that there is little support in the research literature for the widespread (though likely unrealistic) notion of a radical change in science teaching and science learning as a consequence of the introduction of IT in classrooms. This unfulfilled promise of IT in science education has been observed repeatedly, which urges us to conduct a deeper problem analysis of the poor uptake of IT-based research tools in science education.

ANALYSIS OF THE PROBLEM

IT-based research tools, like dataloggers and modeling software, have originally not been designed for use in an educational context. Dataloggers, for example, originated in the physical sciences to take advantage of possibilities of the accurate and automated data collection and storage capacities of computers. In the 1980s, curriculum developers began to modify data logging tools for educational purposes, which yielded applications to be used in the science classroom. Many—if not most—IT-applications currently used in science education followed this pathway. Consequently, many IT-based research tools in science education are originally designed for specific scientific research purposes. Like any scientific tool, IT-based research tools designed for science education can thus be seen as black boxes with a cultural-historical determined inherent body of professional scientific and technological knowledge.

When applied in practical work in school science, the nature of IT-based research tools unavoidably mediates the aims and methods of the curriculum because the different possible applications of a device are constrained by its inherent characteristics. Yet, it often appears that the body of professional scientific and technological knowledge inherent to IT-based research tools is an aim in itself when applied in secondary science curricula. This can be illustrated by the abundance of articles in common journals for science teachers about the application of IT-based research tools in conducting “real” scientific inquiry, that is, doing classical scientific experiments or current IT-based professional scientific inquiry. Such articles are usually written either by enthusiastic curriculum developers who have found a way to imitate “real” scientific inquiry by using common educational IT-based research tools or by professional scientists who illustrate how to conduct their scientific inquiry with IT-based research tools that are affordable for secondary science departments. In this sense, IT-based curricula are often driven by professional science and available state-of-the-art technology. For example, one study expects students to use a number of on-line IT-based research tools for molecular biology, like GenBank, Sequence Manipulation Suite, or GENSCAN that have the aim of providing high school and college students with opportunities of visualizing the impact of “junk” DNA on selected DNA sequences. To be able to “visualize” (interpret) and to meaningfully use these tools, however, the students need a profound body of professional molecular biological knowledge required for the interpretation of what is visualized in the tool (gene sequences as letters, the length
tion of what is visualized in the tool (gene sequences as letters, the length of a DNA/RNA molecule as kilo base pairs, etc.).

Undoubtedly, curricula driven by available technology and professional science are developed with the aim to promote scientific inquiry and, consequently, the understanding of underlying professional scientific concepts. However, one clear outcome of the massive research on students’ ideas in science education is that it takes much effort before students are appropriately introduced to professional scientific conceptual frameworks. Furthermore, researchers have realized for quite some time that students do not invent such frameworks by themselves during practical work, especially if there is no object/motive inviting or necessitating adaptation and change of conceptual frameworks. Rather, students tend to be busy with becoming familiar with the equipment, organizing the experimental setup, doing measurements, record data, and so on. In such a complex learning environment students usually see only what is happening and not why it is happening according a professional scientific theoretical framework. Therefore, like the five physics students who did not “see” the motion of the person around the stool axis (chapter 1), students usually do not see the professional scientific theory in which research activities with IT-tools are framed. For example, it is doubtful if students who are manipulating gene sequences with a series of IT-based research tools, like GenBank, Sequence Manipulation Suite and GENSCAN, will do this with a molecular-biological framework in mind. Rather, it is likely that they are busy with making sense of the websites they encounter while copying and pasting texts consisting of A’s, C’s, G’s, and T’s according to the guidelines provided.

As a result, students cannot fully participate in these research activities and hardly come to understand how and why IT-based research tools are applied in inquiry, nor do they learn the underlying scientific concepts. Instead, practical work easily shifts to obtaining research outcomes without considering the research aims and on learning to operate the research tools, also known as “basic technical skills” or “IT-skills.” It is doubtful whether such skills will be worthwhile as the focus of learning, given that the fast development of IT operations learned today are forgotten tomorrow. Indeed, a focus on IT-skills stems from a view with available technology rather than education in mind. Such a view is inherently a weak rationale, because it will be, in the very end, debited to the poor uptake of IT in education.

Teachers, in turn, tend to apply IT-based research tools in classroom inquiry just to illustrate the professional scientific concepts described by the formal curriculum, rather than to create opportunities for open-ended research. This tendency reinforces a focus on the scientific concepts involved, which further constraints the opportunities to support students’ understanding of the role of IT-based research tools in scientific inquiry. From the perspective of the teacher, the outcomes of IT-supported inquiry-based curricula are usually disappointing because students’ uptake of the scientific concepts prescribed by the formal curriculum is limited and they already master the IT skills they are supposed to learn (at least they perform better than the teacher). More so, such curricula usually take much time and effort.
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to setup. For many teachers, this poor cost-effectiveness relation is a reason to keep the curriculum unchanged and not to do such practical work at all.

Ultimately, the potential of IT-based research tools to transform science curricula is not realized in practice. Indeed, the problem of the poor application of IT-tools in science curricula can be conceptualized as a lack of opportunities for students to participate actively in research. Arguably, this is the case when a rationale for the use of IT-based research tools is based on professional science and available technology. To overcome this problem, a framework for the use of IT-based research tools in science curricula should address students’ active participation in research.

In response to the loosely defined idea of “inquiry-based learning” proposed in science curricula, science educators have produced various and varied rationales for the use of technology in science education focus on students’ participation in research-like activities. However, the proposed approaches commonly focus on learning science in terms of “knowledge,” “concepts,” and “skills” as the aims of research-like activities. This is another example of the inner contradiction we articulated previously (chapter 1), for such terms often stand for the forms of knowing constituting meaningful participation in the research-like activities. Characteristically, such notions articulate the resulting literacies in a static form, which does not correspond to the dynamic nature of authentic scientific literacy inherent to research activity. To enable students to actively participate in scientific research, therefore, science should be treated as praxis, i.e., a human practice with a contingent, dynamic, and indeterminate nature.

CULTURAL-HISTORICAL ACTIVITY THEORY AS A FRAMEWORK FOR THE ROLE OF IT TOOLS

From our problem analysis it follows that to develop understanding of the role of IT-based tools in research students should participate in research activity supported by these tools. A framework for the use of IT-based research tools in science education should therefore focus on the use of tools in science as praxis. Therefore, we reframed this requirement through the perspective of cultural-historical activity theory (CHAT; see also chapter 1) and the inherent notion of human cognition as tool-mediated and object/motive-oriented activity. There are two reasons why this is an appropriate approach. First, CHAT is based on the premise that tools are integral to cognition and therefore of any form of literacy, scientific literacy included. Second, a substantial development in modern activity theory is achieved through studies in human-computer interaction, which focused on the use of computers as tools in human activities. We briefly reiterate essentials of this conceptual framework as needed in this chapter and illustrate how the use of IT-based research tools can support participation in research activity.

We articulate in chapter 1 the ways in which activity theory describes human activity as a collective enterprise with a certain objective. Human activities are for example hunting, farming, caring for the sick, schooling, and scientific research. By performing actions, humans (subjects) participate in the activity system. These
actions are not meaningless but performed with a certain goal determined by the activity system as a whole. As such, the activity system is oriented towards a collective aim, object/motive. Here, the materials at hand and the conditions constitute the object, whereas the anticipated outcome of the production is the motivating motive of the activity. When we look at some specific event, we notice that the subject–object transaction is mediated by the available tools (means of production). A doctor might use his stethoscope for listening an individual’s lungs or heart. Such tools can be of a non-physical nature as well, like language or specific medical knowledge the physician applies for making the person better. Human activities are not uniform, even when oriented to the same objects, but can be done in a particular way (praxis), grounded in tradition, and shared by a community of people who hold it. This also not static, but characterized by sharing it with new members or by means of schooling in which one trains potential members. Participants of an activity are able to shape and reshape the activity, for example by reflecting on the outcomes and, hence, inventing new tools.

IT can support the participation in an activity system at various levels. An appropriate classification of potential ways of supporting human activity by information technology is based on the three-level structure of activity. These three levels, operation, action, and activity, reflect the different organizational levels at which the collective motives of activity are realized (Figure 1.2). At the level of operations, computers can support activity systems by taking over operations. For example, if we enter a dataset in a spreadsheet to calculate the average, a typical number of arithmetical operations, like addition and division, are automated into a routine. At the level of actions, computers can be used to support transformative and manipulative actions and for making tools and procedures visible and comprehensible. Computers and software are consciously chosen to realize the goal set. To continue with our example, a spreadsheet can be used to calculate the average and other kinds of arithmetical routines while organized in a comprehensible sheet so that the user can observe which routines are performed. At the level of the activity systems, computers enable the automation of a new routine or the construction of a new tool. The typical open architecture of spreadsheet programs, for example, allows users to construct and to adjust a worksheet that meets the objectives of research activity and, hence, fits with the research context and methods. Thus, worksheets constructed in research activity reflect the dimensions of the collected dataset, the applied quantitative methods, and the desired representation of the results (table, graph, numbers, etc.).

To fully participate in IT-based research activity, students’ use of IT-based research tools should contribute to research praxis, that is, the lived work of doing science. Students’ use of IT-based research tools therefore should support the objective of the activity at all three levels. At the level of operations, students should collectively be aware of the goal of the action to be performed with IT-based research tools to which the operation contributes so that they can set the conditions of the operation. At the level of actions, students should have a sense of the object/motive of the research activity to meaningfully frame the goals of the action to be performed with IT-based research tools within the research activity. Finally, at
the level of activity, students should be collectively aware of the object/motive of the research activity to the extent that they are able to reflect on the anticipated and achieved outcomes, that is to evaluate the effectiveness of the applied IT-based research tools and, eventually, to set criteria for modifying the applied IT-based research tools or for choosing more appropriate IT-based research tools.

In traditional science education settings in which IT-based research tools are used (Figure 1.3b), students’ participation in the activity at hand usually is not problematic at the level of operations—they follow lab instructions like a recipe without understanding why—and sometimes actions, when they happen to understand the goal to be achieved by the laboratory task. This is because a collective awareness of the goal of the actions to be performed is seen as a very basic prerequisite of classroom education; students usually know what they have to do according to the goals externally set by the teacher. Students do the laboratory tasks to avoid getting low grades rather than to enlarge their control over the learning environment and the range of actions they have to deal with emergent problems. Rather, our rethinking concerns students’ use of IT-based research tools at the level of activity. For this, students’ awareness of the objective at the level of the activity is required, and hence, should enable them to take control of the application of IT-based research tools and to contribute to praxis of research by evaluating and, eventually, modifying the application of these tools.

A CASE STUDY OF STUDENTS’ USE OF IT-BASED RESEARCH TOOLS

To exemplify our rethinking, we reflect on a case study concerning the use of IT-based research tools in physics that one of us (Roth) conducted more than a decade ago. Although some of the IT-based research tools mentioned in the case study may appear as outdated today, it is highly pertinent because students participate in research activity by using various IT-based research tools. Further, this case study represents all the elements of our theoretical framework as sketched previously. We first outline this case study and then articulate how students participated in research activity. The students in this study attended the same private school already featured in chapter 1. More than 90 percent of them were college and university bound, but traditionally selected business related fields of concentration; less than a handful of students went on to study pure sciences or mathematics. The following descriptions of physics classroom activities derive from three classes (14, 16, and 18 students) of introductory physics taught at grade 11.

A Typical Student Investigation

Over the course of a year in this curriculum, there are many experiments that students can do and which, in our case, the students actually did. In all cases, they thought about an interesting phenomenon that they were interested in and then designed on their own, mediated in some instances by the teacher, an experiment that would answer the questions that they had. In terms of the ownership and control over questions and solutions pointed out in chapter 1, these students had them.

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They were therefore in the position to decide what they needed to know to expand their current room to maneuver, that is, what they needed to learn to gain greater control over their problem, their experiment, and their solution. Learning here was expansive, because it was in students’ interest to expand their agency, rather than defensive, which it would be if they were to learn something to avoid being penalized or punished (e.g., by receiving low grades). Table 2.1 shows a small sample of questions that students investigated and which determined the objectives of their research activity. All these experiments permitted the teachers to help students using and understanding the IT-based research tools for bridging the gap between the real world and its representation in the form of mathematical symbols.

As the following case study illustrates, students engaged in using the IT-based research tools. A variety of tools were available to the students for doing research. Among these were graphics calculators, statistical analysis software, mathematics and engineering packages, and programming languages for writing simulations. The use of these tools was indeterminate. Students were free to choose each of the tools to apply in their research activity. The teacher asked them to identify an investigation of their interest and then assisted them in identifying those tools that might help them in finding the answers they were seeking.

The teacher guided the students with the aim to extend their existing abilities with respect to tool use to what they could possibly learn, for example, when a new tool seemed to be appropriate to be included in the research activity, just in time, when students needed some instrumental knowledge to overcome the point when they got stuck, or when there seemed to be an opportunity to develop a new action inherent to the tool use. It must be said that the teacher was given no specific instructions to ensure that tools were implemented in a manner consistent with CHAT. Rather, the primary aim of students’ independent laboratory activities was the participation in research activity—an aim the teacher fully complied with. Any
teacher-guidance was driven by the demands of the investigations and the needs they identified rather than by external demands out of the research community (objectives determined by the curriculum or the teacher). Once one student group began employing a new tool, its use usually spread across the rest of the research community, that is, the class, very quickly.

Because of students’ interest in racing cars and the effect of drag on velocity, the objective of the research activity of one pair of students was to find an answer to the question, “How does the velocity-time graph of an object dropping in a liquid change with the shape of the object?” Since these students had done three experiments on the air track prior to that point, they decided to use the set-up in Figure 2.2 to get their motion data. A picket-fence–like plastic bar interrupted, at regular intervals, a photo gate, which was interfaced with a computer running a datalogging program. The data collected by the computer were plotted, given the characteristic distance from picket to picket, as distance-, velocity-, or acceleration-time graphs. Using the apparatus in Figure 2.2, the students obtained the data plotted in Figure 2.3. Because the graphical analyses packages on the computer were somewhat limited, the students took their data and analyzed them using a different tool, a statistical analysis package with a wide variety of options, among them multiple linear and polynomial regressions (StatVIEW II for Macintosh).

![Figure 2.2. Experimental set up for an investigation of the friction of bodies falling in liquids of different viscosities.](image-url)
The students chose a quadratic polynomial (Figure 2.3) that showed an excellent fit to their data \( R^2 = .999 \). They found a polynomial of degree two for the velocity-time graph of each of their four differently shaped objects. However, while plotting these functions together with a larger range of the independent variable, they realized that the parabolas did not describe the velocity of the objects well: the velocity graphs decreased after a maximum, contrary to the students’ expectation of a terminal velocity. When they came to the teacher for help, he suggested using another tool, a graphics calculator, to explore various mathematical functions.

The students began by exploring other polynomials and root-functions on their graphics calculators. Upon the teacher’s suggestions they also plotted exponential functions. The pupils found that exponential functions, such as \(5^x\) or \(10^x\) showed an asymptotic behavior for which they were looking, but with the negative x-axis as the asymptote. The teacher suggested to the group to explore reflection of the function at the y- and the x-axes in order to achieve a function that had the same general shape as their velocity-time graph (Figure 2.3). After some tinkering and mediated by teacher questions, the three arrived at function of the general type, which is expressed by equation (2.1).

\[
y(x) = a \cdot (1 - b^x)
\]  

(2.1)

Here, the teacher suggested the base “\(e\),” which students had encountered in their eleventh-grade mathematics course. At this point the students were ready to use
another tool of scientists and engineers, MathCAD, which combines the features of a computational tool and that of programming languages.

When the students used MathCAD to plot their data and a hypothesized function, they calculated a measure of goodness-of-fit, RSQ ($R^2$), which indicates the amount of variation in the data accounted for by the function. As the program did not calculate the parameters for a best fit, the students had to estimate the variables terminal velocity ($v_{\text{terminal}}$), initial velocity ($v_{\text{initial}}$), and a frictional parameter ($k$) to fit the function shown in equation (2.2) to the data.

$$v(t) = (v_{\text{terminal}} - v_{\text{initial}}) \cdot (1 - e^{-kt}) + v_{\text{initial}}$$  \hspace{1cm} \text{(2.2)}

After the first trial, the students used the goodness-of-fit index and visual inspection of the graph overlaying the data as feedback to determine the curve of best fit. The teacher had discussed with them the need of some kind of index that would allow them to make the decision about which curve fit the data better when they were confronted with an alternative. He then proposed $R^2$ as one such index that scientists used in their work. Figure 2.4 just shows students’ fit, which, with $R^2 = .996$, was very good.

Before the students wrote up their lab report, they modeled the motion of their object using tools like simple motion equations and a BASIC program. The screen print in Figure 2.5 shows velocity versus time for a system with friction together with the code in BASIC for the simulation. By running simulations with different values for the free parameters, the three students could compare the results of the BASIC program with their measured data: observables such as the gravitational force of the object in the liquid were determined by the students and compared to the values in their simulation. After completing this part of their study, the students
submitted a six-page, typewritten report about their experiment, most of the space devoted to the data analysis, description, and interpretation of the results. All in all, it took the three a standard two weeks to complete this research activity, that is, to meet the research objectives and to submit a report.

STUDENT REACTIONS

There has been an overwhelmingly positive attitude in all the physics classes. Three times during the year, students were given an opportunity to discuss as a class, for a full period, the things they liked about the course, what they disliked, and what changes they would like to see. In addition, students submitted a written evaluation of the course in essay form; and an individualized classroom environment questionnaire was administered.

Preferred and Experienced Classroom Environments

Figure 2.6 shows the means on each of the subscales of the Individualized Classroom Environment Questionnaire (Fraser 1990) both for the preferred and the actual classroom environment. The questionnaire was used to assess students’ attitudes on five scales: Personalization measures the degree of individual attention students perceive (sample item: “The teacher takes personal interest in each student”); Participation measures the degree to which students are involved in classroom discourse (sample item: “Students’ ideas and suggestions are used during classroom discussions”); Independence assesses the degree of students’ independence in managing their classroom environment (sample item: “The teacher decides which students should work together”); Investigation measures the degree to which students use investigations for constructing meaning in the lab (sample item: “Students explain the meaning of statements, diagrams, and graphs”); and Differentia-
tion measures the degree to which students use different learning resources (sample item: “All students do the same work at the same time”).

There were no significant differences between actual and preferred forms on the dimensions of Participation, Independence, Investigation, and Differentiation. These results represent a very favorable evaluation of the approach taken to physics teaching as presented in the present chapter. That is, precisely those dimensions that are associated with individual control and authority—i.e., authenticity, as we defined it in chapter 1—were to the students’ satisfaction. The one significant difference was the dimension of Personalization ($t(39) = -4.04, p < .01$), which indicates that students would like to see more individual attention while working on their laboratory investigations. From the teachers’ point of view, however, there is only a limited amount of time that they can spend with any of the six or seven different projects during any given 40-minute period. The overall positive attitude toward the described physics classroom was highlighted by the essay-type evaluation of the classroom environment.

In their essay-type evaluation, all students highlighted the freedom to choose research topics and the independence in doing the experiments. This provided them with control over their object/motive, which they realized in and through their goal-directed actions. Statements such as “I enjoy the freedom and working on our own,” “I enjoy the freedom to create my own experiments,” “I like the work with the computers,” and “I find it interesting doing these in-class experiments, having different problems to solve and the pleasure in solving them” are representative of the students’ attitude toward the course.

![Figure 2.6. Actual and preferred classroom environments as perceived by the students of the described physics courses on the ICEQ.](image)
Students’ Use of IT-based Research Tools with Respect to the Object/Motive of Research Activity

Seen from the students’ point of view, they were in control of the activity from the beginning to the end. They generated a problem, which did not exist for them before, and completely controlled the problem solving processes. Thus, the students formulated an objective and realized a research activity leading to the desired outcome with respect to this objective. As they proceeded, the students described a physical phenomenon through graphs and mathematical functions making use of different IT-based research tools, in this case datalogging tools, a graphics calculator, statistics software, and programming and analysis tools. The students applied IT-based research tools with the aim to achieve research objectives they framed themselves; and when they did not know some tool that they anticipated to provide them with some advantages, they asked their peers who already used it or the teacher to introduce them to it.

In activity theory, tools are understood as artifacts that embody crystallized operations. In the present instance, we see how this works. Rather than having to do curve fitting by hand, students can test which of a number of functions fits best. Rather than focusing on calculating a best fitting curve or placing one by hand, the operations necessary to do a curve fitting procedure are crystallized in the software. This allows students to focus on higher-order goals, e.g., the comparison between multiple curves rather than focusing on the lower-level skill of calculating a single curve fit.

Here, participation in an investigation did not necessarily mean that students conducted the research activity on their own. For the students, the teacher was an important resource to participate in research activity, showing them the working and possibilities of new research tools. For example, when they faced a new problem—the velocity-time function showed a maximum rather than an asymptote—the teacher suggested and initiated explorations on a graphics calculator. More so, the tools themselves constituted constraints on what can be done and provide opportunities for doing certain rather than other things. In this way, the tools and instruments in addition to the context—this after all was a physics course—mediated what students do and therefore their learning: Students did not just pursue and learn anything but their actions and learning are channeled so to speak.

During the research activity, students contributed to research praxis by evaluating these tools in several instances. For example, the students analyzed the data using a different statistical analysis package (StatVIEW II) rather than using the datalogging package. Apparently, the students evaluated the graphical analyses packages accompanying the datalogging software yielding the decision to use the statistical package, hence to do the research activity in a particular way with respect to the object/motives of research. The contribution to research praxis by the evaluation and decision to research activity in a particular way also counted for the use of the BASIC programming environment as a modeling tool.
CHAPTER 2

INFORMATION TECHNOLOGY AND AUTHENTICITY

From the case study reported in the present chapter, one can observe how participation in research activity implies that students use the IT-based tools with respect to the objectives of research activity. More so, students contribute therewith to the praxis of research by evaluating and, eventually, modifying the application of these tools, also with respect to the objectives of the research activity. Due to the indeterminate, contingent, and distributed nature of such activities, this study does not pretend to provide a reliable forecast of students’ emerging scientific literacy. Some science educators expect such an analysis, that is, an account of the extent to which the implementation of tools in the case study was successful in improving students’ scientific literacy. However, open-ended research activities in congruence with CHAT imply severe problems for determining such measures of success. Rather, we have provided a framework by which science educators can address students’ use of IT-tools in congruence with active participation in research activity. In this sense, we argue for curricula in which the application of IT-based research tools nurtures the development of scientific literacy.

Our framing is fruitful because it allows us to understand why some curriculum applications of IT-based research tools are successful whereas others fail. As pointed out above, virtually any computer tool can be used as research tool. Therefore, whether its use is successful or not in the classroom not only is a matter of the inherent characteristics of the IT-based research tool but rather is a matter of how the tool is applied within the activity at hand. Classroom application of IT-based research tools likely is to fail—that is, failing to contribute to students’ development of scientific literacy—when students are expected to use a particular IT-based research tool as if they perform research activity. This is especially the case when, at the same time, they are not aware of the object/motives of the research activity in which the tools are usually applied and, hence, are not able to apply the IT-based research tools meaningfully in the research activity at hand. This may easily be the case when students conduct complex research activities modeled by professional science while they are not able to understand the research objectives on forehand or when the research activities focus on IT-skills while the research objectives are not made explicit at all. Arguably, the development of scientific literacy will be set back in such classroom applications.

Less obvious, however, is the cause of problems with the use of IT-based research tools when applied in the classroom with curriculum agendas formulated as concepts, formulae, definitions, or, in short, as scientific knowledge. Given our framework, we can understand as well why the use of IT-based research tools may be problematic for the teaching of such curriculum agendas and, as such, may frustrate the development of scientific literacy. To successfully use IT-based research tools and to get a sense of their use in research, students need to understand or have taken up the object/motives of the research activity in which these tools are used. Usually, the scientific concepts to be learned with research activities provide a framework for the meaning and hence, the objectives of the whole research activity. Thus, when applied to learn concepts, students cannot learn the objectives of
the application of the IT-based research tools yet. To teach scientific concepts by means of the use of IT-based research tools therefore implies the so-called learning paradox already described in chapter 1, in which the curriculum design attempts to attribute to the learner prior knowledge that is at least as complex as the new learning to be explained. This problem played a role in a recent design experiment in which IT-based research tools designed for measuring quantities related to the working of the heart were applied with the aim to teach concepts related to the working of the heart. To a certain extent this teaching experiment was successful: students obtained a deeper understanding of common heart-related graphs like the electrocardiogram as compared with traditional textbook-oriented curricula. However, starting from the question how the heart works, it appeared problematic to let students be aware of objectives of the research activity to study the working of the heart. In comparable design experiments it appeared problematic as well to let students pose object/motives for research activities that are meaningful only when the to-be-learned scientific concepts are already known.

To overcome the learning paradox we think about science education in terms of cultural-historical activity theory because traditional views of knowledge, like concepts, skills, formulae, and so on, are in the case of research activity approached as instruments that contribute to the achievement of certain research objectives. To frame such research instruments as “knowledge,” and hence, as a research object/motive rather than a research tool, is therefore an inappropriate account of the very idea of research activity. Rather, all things we know on forehand are instruments to achieve the objectives of our research, that is, to solve a problem or to answer a question, rather than the outcome of the activity, that is, the answer to the problem or question. Expecting students to already know the answer to the problem or question before they conduct research is, indeed, an impossible task (or, as a variant, doing research when students actually already know the answer is a meaningless task).

According to our perspective on the role of IT-based research tools in science curricula, even apparently successful approaches turn out to be problematic. Such approaches can thus be seen as extensive efforts in which an exceptional collection of state-of-the art IT-tools was applied to artificially overcome the learning paradox and to force students to connect their daily-life experiences to particular scientific concepts with the use of IT-based research tools. Therefore, in the use of IT-based research tools to develop scientific literacy, it is important to let students generate problems that do not exist for them before (ill-defined) and to allow them to take complete control over problem-solving processes characteristic of authentic problem solving contexts, where authentic means that the human subject is the authority over and owner of the problem to be solved. By generating this problem, students define the research object/motives themselves, which will lead them to understand the application and working of IT-based research tools and, hence, the development of scientific literacy. Indeed, this is precisely how the students in our case study generated the research goals.

Although students should generate problems, control the problem solving processes and choose IT-based research tools, this does not necessarily mean that they
should work without help from the teacher. Rather, as we have seen from the example, students and teacher may participate together in a common research activity through which the student could practice and, hence, learn to speak the scientific language of the teacher. This form of bringing a newcomer into full participation in a community of shared knowledge through face-to-face talk in the context of ongoing work has been termed cognitive apprenticeship. Such participatory learning relies on the discourse between so-called “experts” and “novices” in a physical and social context similar to that of real world, authentic practice. The context of the on-going student inquiry context provided for a backdrop against which the interlocutors developed their shared interpretation. However, the guidance of the teacher was driven by the internal demands of student inquiries rather than by an external demand such as professional research agendas beyond students’ so-called zone of proximal development (as in the computer episode featured in chapter 1). As such, students applied the new IT-based research tools always in service of achieving the objectives of the research activity.

A shared practice can also extend students’ initial interests and problems they generate. For example, the students had done three experiments on the air track prior to and choose to approach the new problem also by setting up an air track experiment. Commonly, the tools of a field of inquiry drive the questions its practitioners deal with. As such, tools can be also seen as artifacts that enable to students to learn about a particular research practice of research. Indeed, discovering the working of scientific tools without the immediate requirement to generate or to solve problems can be a very rich learning experience. The richness of such learning experiences may count as well for the use of IT-based research tools. Thus, with respect to the development of scientific literacy, an appropriate preparation to the actual generation of problems, which can be ultimately solved with the use of IT-based research tools, may be activities in which students learn some obvious characteristics of such tools. For such activities, just playing with the research tools can be very effective. Indeed, play can be viewed as a means by which children could enter their zone of proximal development so that they could practice more mature behavior. Accordingly, play can be useful as a way of discovering the characteristics of IT-based research tools and mature behavior might be in this case the application of tools with particular research objectives in mind. Entering the zone of proximal development in this way will ultimately contribute to students’ ability to pose meaningful research questions with respect to the working of the IT-based research tools, and, subsequently, to develop scientific literacy while actually applying the IT-based research tools in research activity and contributing therewith to research praxis.