Science, Culture, and the Emergence of Language

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Received 4 January 2000; revised 3 January 2001; accepted 15 March 2001

ABSTRACT: A major achievement in the sociology and philosophy of science over the past two decades has been the recognition that science is a form of culture with its own creeds, language, material practices, perceptions, theories, and beliefs. Learning science then amounts to participation (from more peripheral to central ways) in the particular practices of this culture. We argue here that there are some fundamental, heretofore neglected, ways in which newcomers come to perceive and talk about natural phenomena. Beginning with "muddled" talk and supported by deictic and iconic gestures, learners isolate salient objects and events which are, in increasing ways, represented in linguistic forms. More abstract forms of communication (writing, abstract symbols) are competently used only later in the emerging communicative patterns. As such, there lies tremendous potential in science activities that focus on observational and theoretical language in the presence of the relevant phenomena. *Sci Ed* **86:**368–385, 2002; Published online in Wiley Interscience (www.interscience.wiley.com). DOI 10.1002/sce.10008

Worldmaking as we know it always starts from worlds already on hand;
the making is a remaking

Goodman, 1978, p. 6

INTRODUCTION

In this paper we explore the connection between worldmaking and our own bodies in an attempt to open a discussion regarding how a hands-on approach to science education

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Contract grant sponsor: Social Studies and Humanities Research Council of Canada (SSHRC).
Contract grant number: 410-99-0021.
Contract grant sponsor: University of Victoria.

facilitates the emergence of scientific communication through gesture. We begin by twisting Goodman's statement to the point where much of the connotation is squeezed away leaving only the suggestion that making a world (in this case, making a scientific community) begins with those things on hand. Worldmaking, as thinking (Heidegger, 1977), literally is handwork. From this, we suggest that there is an intrinsic link between scientific observational and theoretical language, the physical manipulation of natural objects, and the gestures of scientists. We hypothesize that a similar link might be found among the talk and gestures of science students and provide case studies to make this hypothesis plausible.

We structure our argument as follows. First, we set the stage by articulating science as culture strongly characterized by its language. Second, we sketch the literature on language emergence at the level of scientific culture and individual, with a particular focus on the role of manipulation and gesture in this emergence. Third, because language emergence and gesture studies are virtually absent in the (science) education literature, we provide two concrete case studies of language emergence in relation to gestures and manipulations of equipment. These case studies, exemplars of a large database that we have accumulated over the past decade, support our contention that the study of gesture and language evolution in science education is a worthwhile endeavor. And finally, in our concluding section, we outline the tremendous opportunities that lie in asking students to describe and explain phenomena in the presence of materials and equipment.

SCIENCE AS CULTURE

Mannheim's sociology of knowledge is premised upon the idea that "there are modes of thought which cannot be adequately understood as long as their social origins are obscured" (Mannheim, 1936/1966, p. 2). From this perspective, the construction of knowledge can be seen as a social activity. In other words, it is constructed by "men [and women] in certain groups who have developed a particular style of thought" (p. 3). As such, Mannheim emphasizes the role of the group in the construction and maintenance of knowledge and downplays the role of the isolated individual. It is not surprising, then, that science has come to be recognized as a form of culture with its own creeds, language, material practices, perceptions, theories, and beliefs (Fuller, 1997). This shift towards viewing science as culture has been facilitated by an increasing interest in scientific practice from disciplines traditionally concerned with cultures and subcultures. Researchers from these disciplines, including sociology, ethnography, and anthropology, have adopted the methodologies of inquiry honed in cross-cultural studies and applied them in the laboratories of science (e.g., Latour & Woolgar, 1986; Traweek, 1988).

In the wake of Kuhn's seminal work, researchers have come to associate scientific culture with specific social, material, linguistic, and rhetorical practices (Kuhn, 1962). Consequently, an increasing number of researchers have focused on the role of language in the construction of scientific cultures (e.g., Bazerman, 1987). However, along with linguistic conventions, there are other practices that contribute to this development, including visual, gestural, and manipulative activities (Lemke, in press). For example, a number of studies have marked the transformation of language as it moves from the uncertainty embedded in initial observation statements, to propositions constructed during laboratory conversations, to a statement of observation as an unassailable scientific fact (e.g., Amann & Knorr-Cetina, 1990; Latour & Woolgar, 1986; Roth & Bowen, 1999a).

Microanalytic studies that document and theorize the emergence of new observational and theoretical descriptions are scarce. (The study of astronomers in the process of discovering a new celestial object is one exception [Garfinkel, Lynch, & Livingston, 1981].) However, there exist several historical studies that have attempted to document and theorize the emergence of new language from the moment-to-moment activities of past and present researchers (Gooding, 1990; Pickering, 1995). More importantly for our purposes, both Gooding and Pickering provide clear indications that language emergence is deeply caught up in material practice. That is, there is a codependent emergence of the nature of the objects scientists see (observational descriptions) and manipulate, their technical know-how, their descriptions of the apparatus, and their theoretical descriptions of the phenomena.

Given this connection between scientists' observational and theoretical descriptions, on the one hand, and material activities and manipulations of equipment, on the other, we may expect similar relationships among school-aged learners. However, only a few microanalytic studies have explored how conceptual talk (at Piaget's "formal" level) is linked to students' interactions with the physical world (e.g., Roth & Duit, 1997). In this paper, we argue that there are some fundamental processes in the emergence of observational and theoretical language involving manipulations that give rise to gestures, which themselves support the emergence of language.

LANGUAGE, GESTURES, AND MANIPULATIONS

The role of gesture and manipulation in the initial emergence of language has long been recognized (Miller, 1981). That is, before children develop their first words they can spontaneously pick up objects and present them to adults. Thereupon, communication skills, through the manipulation of objects, begin to develop long before linguistic competence.

In this section, we sketch out our argument about the emergence of scientific language from the initial "(inconclusive) muddle" (Rorty, 1989, p. 6) that can be observed among scientists and students. In the process, hand movements play a crucial role. Initially concerned with manipulating and sensing objects in the world, these movements evolve into symbolic gestures and ultimately, viable descriptive and theoretical language.

From Muddle to Mature Language

The creation of a new form of cultural life, a new vocabulary,
will have its utility explained only retrospectively

Rorty, 1989, p. 55

During the decade or two following Kuhn's publication of *The Structure of Scientific Revolutions* (Kuhn, 1962), some historians of science conceptualized theory evolution in terms of revolutions, connoting more or less sudden changes in the way phenomena are described in observational and theoretical terms. More recent treatments suggest a range of processes, only a small minority of which consists of radical, sudden change (e.g., Chi, 1991; Churchland, 1989; Thagard, 1996).[1] Because of observations during a decade of microanalytic work on classroom science discourse, those theories that focus on almost imperceptible changes in the language used in observation and theory descriptions are of particular interest to us. For example, Rorty (1989) suggested that during the transition from the Ptolemaic to the Copernican world view, the talk of scientists, church elders, and others was more like "inconclusive muddle." (Here, muddle is a positive descriptive term.) Out of

[1]Thagard (1996) provides a table in which he articulates nine degrees of concept modification. Only "branch jumping" in and "tree switching" of conceptual frameworks may be consistent with a discontinuity hypothesis; tree switching is compatible with radical (ontological) change (Chi, 1991) and gestalt switch (Fuller, 1992). Based on a neurocomputational perspective, Churchland (1992) suggests that conceptual discontinuities are rare and most often consist of "conceptual redeployment," which we understand to be an instance of "tree switching."

this muddle, emerged the new, internally consistent Copernican language for talking about celestial phenomena. However, there are neither internal (to language) nor external criteria (nature) that can *explain* this new language; the new language is an emergent phenomenon. In recent years, studies by Gooding (1990) and Pickering (1995) have highlighted the nature of new scientific observational and theoretical language as an emergent phenomenon. Both studies show, in painstaking detail, how experimentation (as a situated form of learning) involves the manipulation of conceptual and material objects. Through mutual adjustment and processes of resistance and accommodation, conceptual and material objects coevolve into new mutually constitutive entities that are reified in language. That is, new theoretical and observational languages coemerge in a process mediated by the material agency of the experimenter. During this process, much of what is talked about is uncertain (does not have a definite status) so that the language is highly ambiguous when viewed from an a-posteriori perspective. It is only after the fact, when scientists have come to a new structure, that they reconstruct their narratives for demonstrative (e.g., publication) and pedagogical purposes (Gooding, 1992).

Quine (1995) sketched a possible trajectory for the emergence of scientific language from the physical stimuli of the body. Beginning with perceptual similarity of salient objects, which are first fixed by sweeping (iconic) or pointing (deictic) gestures in the vicinity or direction of the focal scene, the trajectory concludes in mature scientific language. In the evolution of scientific language, two or more simple observation sentences (e.g., “It’s raining” and “There is a cloud”) come to be correlated into observation categoricals (e.g., “When it’s raining, there is a cloud”). In the transition to more focused observational categoricals (e.g., “Whenever it’s raining there are clouds”) we have the foundation of a theoretical language.

From Manipulations to Gestures

Gooding (1990) and Pickering (1995) emphasize the central role of human agency, particularly the manipulations of objects and equipment, in the structure of emergent observational and theoretical languages. At the same time, a different feature of communication, gesture, is an observable feature in scientific laboratory communication (Goodwin, 1995; Ochs, Gonzales, & Jacoby, 1996; Woolgar, 1990). Without recourse to deictic (pointing) and iconic (sweeping) gestures, scientists would find it difficult to communicate. Similar work among middle and high school students suggests that gestures are not only an integral part in students’ (proto) scientific language, but that these gestures actually facilitate the emergence of scientific language (Roth, 1996a, 1996b).

Gestures, therefore, play an important role in scientific laboratory talk. Our review, then, shows that different classes of movements—manipulations (“ergotic movements” (Cadoz, 1994)), sensing (“epistemic movements” [Weissberg, 1999]), and gestures (“symbolic movements” [Roth, in press-b])—are related to scientific language.[2] Yet, we have not found one study concerning the relationship between the three different forms of movements in scientific discourse. However, there is evidence from the brain sciences that neuronal assemblies responsible for language make use of neuronal assemblies that previously developed first in response to human movements and later took on gestural functions (Bates, 1999). With respect to language in general (Goldin-Meadow, Alibali, & Church, 1993) and scientific language more specifically, there is evidence that gestures might perform a transitional function between the ergotic and epistemic movements, on the one hand, and mature scientific language on the other (Roth, 1999a, 1999b, in press-a).

[2] Objects may be manipulated to facilitate perception, recognition, thinking, planning, and so forth. Such manipulations have also been termed “epistemic” (Kirsh & Maglio, 1994).

Ergotic, epistemic, and symbolic movements are important aspects of cognition in all cultures (Kendon, 1997). In fact, studies among Australian aborigines and African bushmen tribes documented a deep interdependence of body movement, gesture, language, and other aspects of cognition (Haviland, 1993; Levinson, 1997; Widlok, 1997). Thus, to account for the orientation feats accomplished by members of these cultures, gestures, narratives, and bodily action form an irreducible system of cognition. Furthermore, across cultures, the relation between gesture and language is so profound that even congenitally blind people will use gestures not only with seeing but also with other blind interlocutors (Iverson & Goldin-Meadow, 1998). Our review brings us to an important point, which, if confirmed in further research, has tremendous implications for learning scientific language in science classrooms. If gestures arise from laboratory manipulations and if gestures have a function in the emergence of scientific language, then they can be seen to represent an important transitional step in the development of a scientific discourse. In the following section, we provide two case studies that illustrate the emergence of language from, and supported by, manipulations of objects and subsequent gestures.

CASE STUDIES OF LANGUAGE EMERGENCE IN SCIENCE CLASSROOMS

The case studies presented in this section derive from an extensive database that includes more than a dozen studies of learning in school science laboratories in four countries (Australia, Canada, Germany, and the United States). In each study, two to three student groups were videotaped over an entire unit lasting from 3 to 16 weeks. The following cases exemplify patterns that hold across the different studies. The first case study comes from a grade-12 physics class in Canada in which 20% of the students came from various Asian countries to get their high school certificates, and the remainder of the students were of various European and Asian descent. The second case study was recorded in a German grade-10 physics class.

From Confused Muddle to Theory

The following episode features three students, Elizabeth, Glen, and Ryan, working with a computer-based Newtonian microworld (Interactive Physics™) as part of their grade-12 physics course. They have already observed repeatedly the circular object and the two associated arrows. Their task is to determine the relationship of the arrows to the motion patterns displayed by the onscreen object (Figure 1).

Glen proposes a description in which the “big arrow” and time are the same (lines 01–02); Ryan suggests that they should run another experiment in which this big arrow is shorter (line 03). Elizabeth (line 04) and Glen (lines 05–06) propose alternative referents for the two arrows (“time” and “direction”); Ryan attempts a synthesis, but his use of “though” (line 09) indicates potential trouble. Elizabeth tentatively formulates a referent for the “little arrow” (lines 10–11), but Ryan suggests that they do not know that referent. Glen then provides an observational description of the little arrow: “it always stays straight” (line 13). He simultaneously uses his pen in an iconic gestures that makes salient the direction of the arrow that stays straight.

Here, the language is best described by our concept of “muddle.” Students use the same terms (“big arrow” and “little arrow”), but, as it turns out later, the three students did not realize for some time that the referent of “little arrow” and “big arrow” were different. That is, because “big” also connotes long or tall, the adjective was used to denote both the

01 G: Oh yeah the big arrow's time, 'K (1.2) the
02 big arrow's time.
03 R: OK, we'll make it shorter.
04 E: So then the little arrow is direction. (1.3)
05 G: Yeah the big arrow is direction. No I mean
06 the big arrow is velocity—
07 E: —It's, time—
08 R: —No, it's
09 time but it also directs, though.
10 E: Yeah and then the little arrow, no the little,
11 isn't the little arrow. (2.1)
12 R: We don't know yet.
13 G: The little arrow always stays straight.

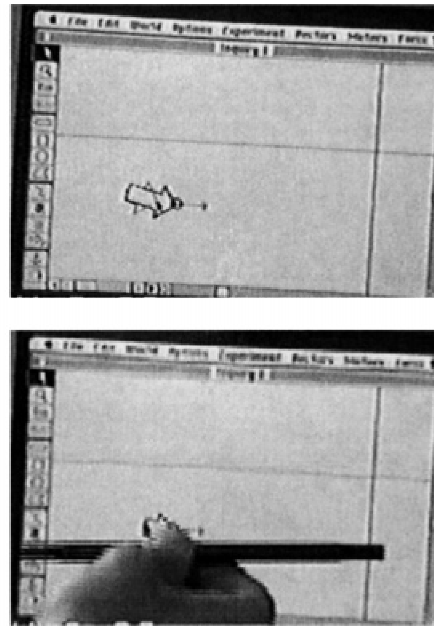
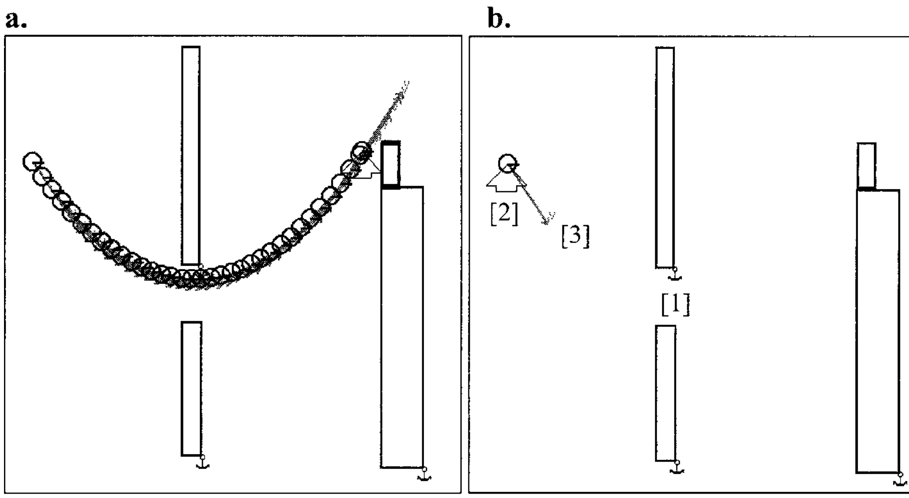


Figure 1. Episode from a lesson in which students attempt to find out the relationship between the two arrows and the circular object by conducting experiments with different arrow sizes and directions.

«force» arrow and the «velocity» arrow.[3] In addition, students make reference to different observations by using the same word, "direction," to index different observations. Thus, the trajectory is initially parallel to «velocity» but toward the end of the trajectory, it is parallel to «force». When Elizabeth talks about the little arrow representing direction (line 04), Glen, though he at first contradicts her, then proposes a label of "velocity" for the "big arrow." As it turns out, throughout this lesson, the three students employ up to 10 different words to talk about the same object. For example, the three students referred to «force» using any item from the set {little arrow, big arrow, time set, time, direction, time & direction, velocity, redirection, gravity, force} before they ultimately settle for "force." They also used 11 different words to denote «velocity» until they settled for "velocity." In other groups, we made the same observations (Roth, 1996a). Overall, this episode exemplifies the beginning of students' communications when they are unfamiliar with a given domain; their language appears brief, incoherent, inconclusive, and (from an observer's perspective) continuously changing in topic. Most novice researchers do not know where to begin an analysis of such episodes.

In this simple (micro) world, there are only a few objects. Yet in the conversations of this student group (as well as the other groups in the class), what is being talked about, as well as the words used to denote whatever is being denoted, differ—without the students' awareness. As a result, many observers of these and similar episodes are taken aback and propose that these students have some cognitive deficit, misconceptions, do not show enough effort, and the like. Such explanations may be viable if it were not for the fact that we recorded structurally similar episodes in studies of physics learning in four different

[3]To avoid confusion in the changing referents and lexical items for the same things, we identify the object in terms of the standard definition within physics discourse. The outline arrow represents force and is identified here as «force» and the single line arrow which represents velocity is denoted by «velocity» in our text.



01 **Glen:** See cause you know how your force is going this way [UP], but
02 once it hits that place [1], it stops in the air. And then you know, a
03 basketball, once it hits the top of your arc, you want it to go down
04 right? So you put the tip put the bottom over here [2], then you have to
05 have this really long over up here [3]. You want the velocity like a lot
06 longer. Go to . . . click the circle!

Figure 2. Episode from a lesson in which one student uses a mature form of school science talk to describe and explain the on-screen events.

countries, including the best students (valedictorians and the like) in each case (e.g., Roth et al., 1997a; Roth & Duit, 1997; Roth & Roychoudhury, 1992). Moreover, just as intriguing is the observation that we find the same type of “muddled” talk in studies of scientists when they work in domains with which they are not very familiar (Roth & Bowen, 2001). However, when individuals have considerable time to familiarize themselves with the domain at hand, we find them at some later point talking in coherent ways, with certainty, and consistent discourse about the objects and events in the focal phenomena.

To provide some evidence of such a shift, let us return to the same three students. About two weeks after the previous episode that included about two more hours of interaction with the Newtonian microworld, the three are working on a task which asked them to hit a rectangle on a post, requiring the circular object to move through the hole in the wall (Figure 2). After having tinkered for a while with «force» and «velocity», the three observe the object moving through the hole as in Figure 2a. Glen then provides a description that mixes observational and theoretical terms to plan their next move. Thus, he first identifies «force» as force (line 01) and then likens the situation to a basketball throw where the ball, at the “top of the arc,” appears to “stop in the air.” To get a similar effect, he then proposes how to reorient «force» and «velocity» to get the object to move through the desired trajectory to hit the rectangle. He finishes his turn by suggesting how velocity can be changed by clicking the object (lines 05–06).

In this episode, we see no more hesitation and the use of signifiers is consistent with standard physics. Glen still uses a considerable number of deictic (pointing) and iconic gestures, which can almost always be observed when the objects of the discussion are present in the situation. (We address the relation between verbal and written language in the next section.) Importantly, because students talked over and about the entities on the screen, they could employ deictic (for pointing) and iconic (for sweeping) gestures. As the video offprint in line 13 (Figure 1) shows, there is an interaction between the gesture (pen) and the image behind it. The utterance “The little arrow always stays straight” and the direction of the pen in fact tell the listeners to look for something that stays straight and its direction. In the present case, there are two arrows that are in approximately the same direction. However, the adverb “always” allows listeners to draw on the previous experiments in which one of the two arrows always remained in the same direction.

In contrasting these two episodes, we see that, beginning with initially almost incomprehensible talk, students developed observational and theoretical language for the phenomenon at hand. How students move from the initial “muddle” (which we use without negative connotations) to mature science talk is a question virtually unaddressed in science education. Furthermore, by using the concept of “muddle,” we highlight the tremendous challenges faced by students during learning when they have to move from where they are to where curriculum designers and teachers want them to go. As such, one of the central questions regarding the development of scientific concepts has to be how students get from muddle to scientific discourse. In the following section, we provide two analyses how language evolves when students engage in laboratory activities.

From Moving Things to Talking (and Writing) Science

In our long-term studies, we are interested in following students from their initial encounter with new phenomena to the point where they had developed a viable discourse about them. Here, we are concerned with science laboratory activities that require students not only to conduct investigations but also to construct observational and theoretical descriptions. In this section, we use excerpts from one study to exemplify the data obtained in these studies and our more recent theoretical understandings of these data. (Additional development and application of these ideas can be found in Roth, 1999a, 1999b, 2000, in press-a.)

The following episodes exemplify the evolution of observational and theoretical talk as it becomes increasingly independent from the material aspects of the activities. The context for these episodes is a pith ball and rod experiment intended for students to develop observational and theoretical languages of electrostatic induction. (See the Appendix for a description and standard explanation of this typical high school physics investigation.) This evolution can be glossed in the following manner. Students begin their first explanations by reenacting parts (or all) of an investigation which serve as topic of and background to their utterances. In subsequent attempts, the materials and equipment still function as ground but gestures begin to replace actual objects and events. In the next stage, students frequently employ a different object or gesture only to represent some relevant aspect of the event they talked about, and finally they represent all relevant aspects of objects and events in symbolic (abstract) form.

In the course of their activity, which extends over two 45–min lessons, Matt and Phil make six clearly distinguishable attempts to construct an explanation. Excerpts from three of these explanations are featured in Figure 3. Initially, students rely almost exclusively on redoing the investigations as part of their attempts to provide a description of the phenomenon and as a context for constructing observational and theoretical descriptions (Figure 3a). At this point, they had repeated the investigation (as described in the Appendix) several times. Next, they decide to write down their observations and explain what they see. However, during this episode, they find themselves stymied and incapable of expressing themselves in writing. Rather than writing, they return to the equipment and Phil begins to build a description as he conducts the investigation again. He begins by discharging the pith ball (Figure 3a.i) uttering “discharging” and then brings a ruler, which he had charged by pulling it between his knees, close to the metal rod uttering “we now hold it here” (Figure 3a.ii).

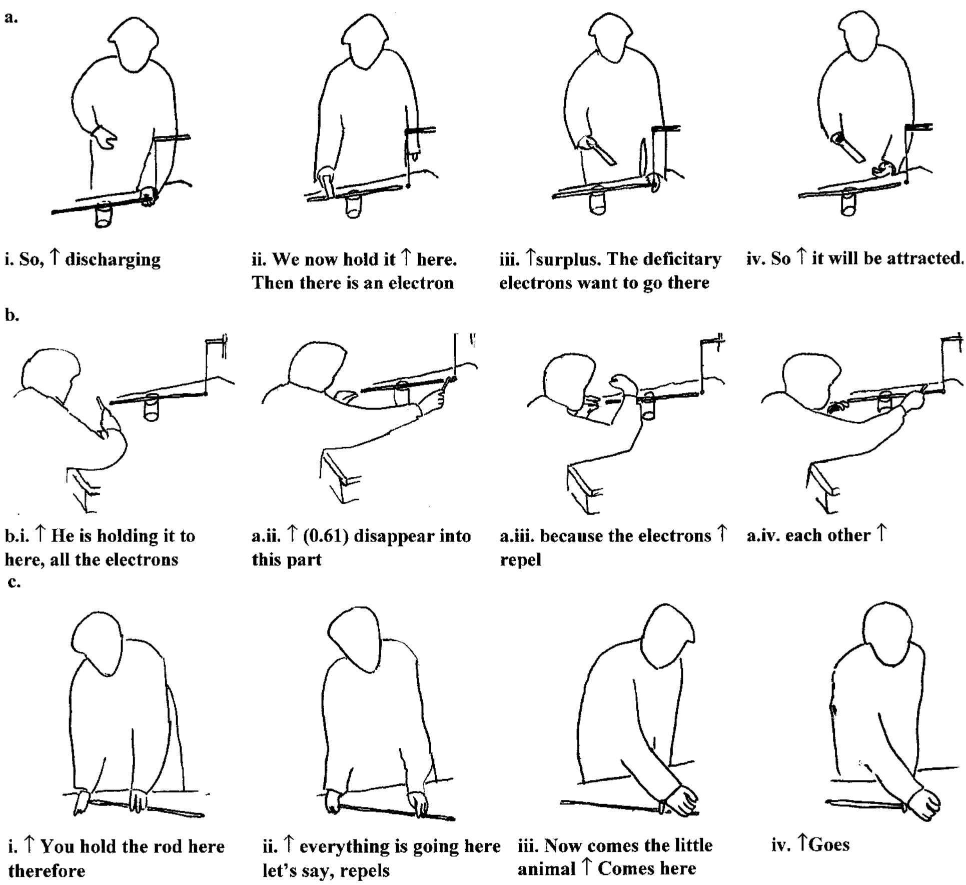


Figure 3. Three episodes from a classroom in which students are asked to conduct, then describe and explain the rod and pith ball investigation in order to evolve a language about electrostatics.

As the pith ball begins to bounce, he points toward the end of the rod while beginning a theoretical description on the basis of electron surplus (Figure 3a.iii). He then introduces a nonword "deficitary" (they use a neologism, "unterschüßigen," that does not exist in German) electrons, which want to go "there" and then moves his left hand parallel to the direction of the pith ball/metal rod axis.

In this episode, Phil repeats the investigation, including metaphorical-iconic gestures that enact the theoretical objects (electrons). The presence of the material and equipment allows a description, as a naming of objects and actions. (In evolutionary and developmental terms, this comes prior to language that is independent of the objects.) That is, repeating the investigation so that it is there, in front of everybody's eyes, makes a detailed and explicit description unnecessary. It is a general phenomenon of everyday interaction that what goes without saying remains unexpressed (e.g., Clark, 1996).

Because the associated events are most often too fast (such as the bouncing pith ball in this investigation), students simulate the events by moving the objects through the different stages of the phenomenon. This allows students to describe the observed objects and unfolding (simulated) events in real time allowing for a copresence of expressive means (words, gestures) and the aspects of the world they perceive. This stage of learning is exemplified in Figure 3b. Here, Matt describes the events while his hand reenacts the same movements that had earlier charged the ruler and brought it close to the metal rod (Figure 3b.i). But now, he no longer charges the object; the apparatus is simply the background against which his gestures are to be seen. His subsequent gesture and talk invoke electrons as the theoretical entities, which, in a metaphorical way, are said to move in parts of the equipment (Figure 3b.ii–iv). His right hand enacts the movement of the electrons in the rod which, because the electrons are presumed to be the charges in the charged ruler, are repelled and move to the opposing end in the metal rod.

In what becomes the next phase of constructing observational and theoretical descriptions, objects other than those involved in the investigation are used in a representational manner. A piece of paper comes to stand for a transparency film; two pens are used to represent two materials; and a third fountain pen with removable cap is used to model the separation of nucleus and electrons (see Roth (in press-a) for further details). This was also the case in the work of Phil and Matt (Figure 3c). Phil had picked up a plastic rod, which, as the unfolding presentation shows, stands for the metal rod in the earlier set-up. This rod provides a representational ground against which other parts of the equipment and theoretical entities appear in the form of gestures. This allows listeners to understand Phil, although his talk is highly indexical as he describes the preparation of the phenomenon with the words "you hold the rod here" (Figure 3c.i). This utterance is accompanied by a gesture of the right hand close to the right end (from his perspective) of the plastic rod. From his perspective, this orientation is the same that he had earlier with respect to the apparatus, and the right hand took the same position in which both he and Matt had held the charged object. His right hand then moves toward the left end of the rod while uttering that the theoretical entities ("everything") is going there (Figure 3c.ii). The subsequent frames (Figure 3c.iii, iv) show his description of how the pith ball ("the little animal") approaches the end of the rod ("comes here").

There are a number of typical dimensions for the early stages of communicative competence (cognitive complexity and temporal aspects are discussed in subsequent sections). First, students use equipment and materials that they describe in observational terms. Second, their conceptual talk is often scientifically inappropriate. Third, in the early stages, students often speak from the point of view of the inanimate entities involved and thereby portray these entities as animate. Fourth, human agents draw heavily on verbal and gestural indexing (linguists refer to this as verbal and gestural "deixis"). In the early phases, the materials and the equipment serve as ground and, in some cases, are replaced with arbitrary objects. For example, Matt replaced the original ruler with a pencil (Figure 3b.i), which subsequently served mainly as a pointer. The presence of these materials (or their substitues) affords students to point to particular aspects without generating the corresponding words to signify them. Matt does not name the iron rod other than in Figure 3b, though he refers to it repeatedly as part of his presentation. Also, he does not name the pith ball, but only refers to the object as "this" or "it" usually accompanied by pointing (gestural deixis). "Here" is relative to the position of the hand and where he is located as the observer positioning (linguistically, this is described in the term "origo"). The point of view is holistic in the sense that objects and subjects are not separate, but immersed together in a shared world. (Researchers have come to use anthropomorphism for descriptions of the world emerging from this immersion.)

In the subsequent phase, students used some of the materials from their investigations as ground against which they layered their theoretical descriptions. We can conceptualize the deictic and iconic gestures as participating in enacting a Gedanken ("thought") experiment, but a Gedanken experiment enacted in concrete terms with worldly objects. While students conducted the investigation or moved parts of the equipment literally around as part of describing what happens and constructing a theoretical description in the previous event, they now simply use talk and gestures in one communicative act.

When students become very familiar with the objects, equipment, and phenomena produced with them, their attempts to explain no longer require the presence of the materials.

At this point, we see arbitrary objects as signs that stand for some object or entity. For example, in an explanation of how static electricity is produced, one student, Jessica, uses two pens to represent the two materials to be rubbed. A third, fountain pen stands for an atom, which, as part of the rubbing, is separated into a positively charged nucleus and negatively charged electrons. Her iconic gestures enact the separation by pulling the cap off the pen, while her verbal and gestural deixis associate each of the entities with the corresponding macroscopic materials. In a similar way, toward the end of the second lesson spent on the steel-rod–pith-ball investigation, another student, Phil, produces an explanation in which he only uses an arbitrary PVC rod to stand for the steel rod.

As students become more familiar with the phenomenon and with talking about it, their language increasingly represents the entire phenomenon.

> This is the stand. There is a little ball of elderberry mark, it is neutral, uncharged, and coated with graphite. Here, this one is an iron rod, a conductor. Now we thought about a trick. The task was posed in this way: construct the set-up in this way, and then bring a charged plastic ruler close to the end. [Matt, JU6p.15]

Compared to the earlier episode, in this excerpt an increasing number of aspects relevant to the phenomenon are articulated. No longer do the materials only stand for themselves visually available to all (though this is still the case), but they are re-presented in the verbal description. Thus, in the case of the little ball that students had seen bouncing back and forth, its material (elderberry mark), coating, and electrical property are all articulated.

The sequence of episodes illustrates how students become increasingly independent of the actual objects and equipment in the production of their observational and theoretical descriptions. There is an abstraction from the actual phenomenon to the simulated phenomenon with the actual objects, to a simulation where the objects themselves are replaced by other, arbitrary objects (Figure 4). We observed a progression from iconic representations of phenomenal entities to more abstract representations of objects and events. (An analoguous progression was observed in the notes, compositions, and drawings of grade 4–5 students (Roth, 2000).) Thus, these grade-10 students initially represented their investigations and explanations of phenomena by depicting objects and events and subsequently used increasingly abstract signs to stand for the same entities. Here, the initial stages are exemplified in the depiction of rubbing materials and a little person holding a neon lamp to the charged film (Figure 4a). At later stages, the same phenomenon is represented by single charges (rather than films) and the icon—“hand” combination rather than the entire person (Figure 4b.left). Less graphic still is the subsequent sketch in which ground (“Erde”) and light bulb are depicted by symbols from the electrotechnical domain.

To summarize, in situations such as these, language emerges by taking on an increasing amount of representational function from other modalities. These other modalities include the world itself, gestures that both pick out objects and enact them, and objects standing in for other objects. Furthermore, although students’ ultimate task is to produce written (observational and theoretical) descriptions, these come only very late (literally at the last minute); gestural, verbal, and pictorial expressive modes precede written language. Simultaneously, we observe a shift from depiction and iconic representation to abstract sign and from descriptive expressive modes to theoretical (explaining) modes.

We assume that what students do in these episodes is, first and foremost, enact a telling of world through the manipulation of both the material objects and language. In their absorbed activity, they are coping rather than theorizing. When students use gestures, for example, to point at an object, they articulate the world in two ways: (1) they indicate the joints

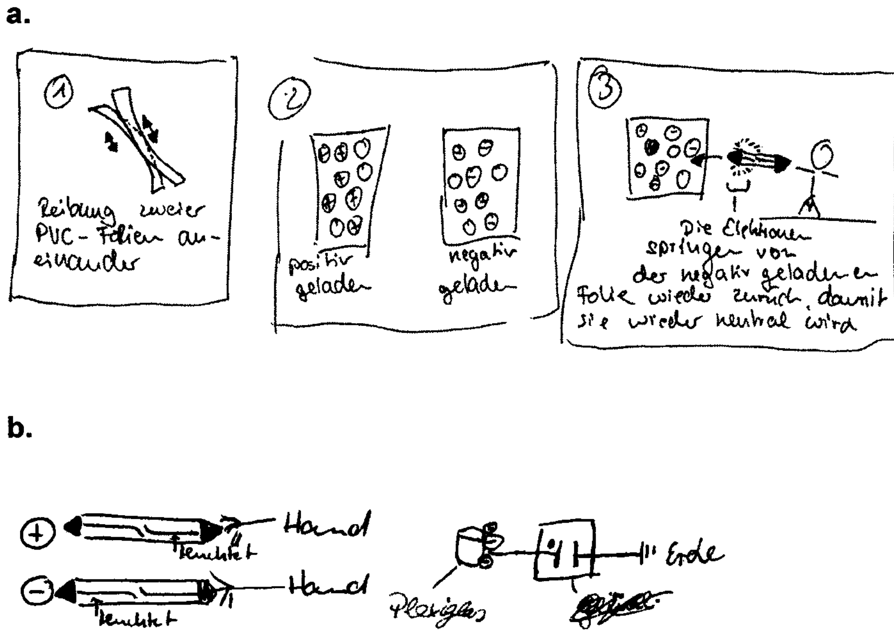


Figure 4. The evolution of increasingly abstract forms of representing scientific phenomena also occurs in the written modalities. a. Initially, students use more depictions and iconic representations. b. Later, they increasingly use representational forms that no longer have iconic relations with the objects and events they explain.

where it is carved into wholes and parts and (2) they "tell" these wholes and parts. Telling, as gesturing, gestates or makes world. In this sense, these students' gestures allow them to pick out the object in the way small children pick out the chair by uttering "chair" in the presence of the object «chair». In this sense, telling is equivalent to primary human observation sentences or bird calls and monkey cries that occur in the presence of a tiger. This way of regarding telling as primordial is equivalent to the view of the observer in cybernetics: telling is first-order observing (Lock, 1997). Theorizing, on the other hand, is second-order observing, as the subject begins to tell the similarities across observations not only of other observers but also his own; theorizing, as interpreting, requires hypothesis formulation and testing (e.g., Luhmann, 1995). It is, therefore, only after the fact (when they competently discourse in the language of science) that students can evaluate different ways of talking about a phenomenon.

HANDS-ON ACTIVITIES: "FROM STIMULUS TO SCIENCE"

In *From Stimulus to Science*, Quine (1995) outlined how conceptual languages could develop from raw stimuli at the human sensori periphery. The itinerary outlined in this book was largely confirmed in synthetic modeling experiments with robots that had to learn not only language but also the nature of the world they inhabited (de Jong, 2000; Steels, 1997; Vogt, 2000).[4] Our microanalytic studies of language development in school science

[4]The robots are equipped with a minimum of motion and communication primitives. They are then let loose in a (simple) environment where they learn, by moving about, to make their world. If they do not do this in a viable way (e.g., not find food by docking into a recharging device), they will die. In this way, each robot makes its own world. When there are two or more robots, they (perceive and) react differently to what

laboratories, as exemplified in the previous section, suggest that similar processes may be in operation. If future research substantiates our early findings and hypotheses, there will be substantial implications to science education. In this section, we briefly discuss possible implications to science education, particularly the role of hands-on activities that afford language development via manipulations and gestures.

We began this paper with the premise that science itself is a culture with its own particular narrative forms, material practices, beliefs, etc. Viewed in this way, learning science is equivalent to other forms of acculturation, including participation (from more peripheral to central ways) in the particular practices of this culture. A number of cultural studies of science have documented the trajectories along which graduate students increase their participation in the core practices of science, particularly the representational (linguistic and otherwise) practices (e.g., Roth & Bowen, 1999b, in press, 1999c; Traweek, 1988). One of the central aspects of culture, however, is language. This point is emphasized in Lemke's seminal work (Lemke, 1990), *Talking Science*, in which the relationship between science (as culture) and language is brought into focus:

> Learning science means learning to talk science . . . "Talking science" means observing, describing, comparing, classifying, analyzing, discussing, hypothesizing, theorizing, questioning, challenging, arguing, designing experiments, following procedures, judging, evaluating, deciding, concluding, generalizing, reporting, writing, lecturing, and teaching in and through the language of science. (p. 1)

Lemke suggests that language is not simply a medium that stands between students' minds but is a constitutive aspect of the activities of observing, describing, comparing, and so on. In addition to language, we have tried to make salient the role of manipulations and gestures in the development of scientific language. More specifically, we showed the mediational role gestures assume between language and world in a double sense. First, gestures are an important component in the transition from manipulations to language; and second, gestures also ground (connect) verbal utterances to the objects that they are said to be about.

First, "hands-on learning" has been a slogan, but there exists a lack of research to show how conceptual ("abstract") understandings arise from manipulating things in the physical world. Our own work, from which the present case studies are taken, shows how hands-on learning affords new forms of observational and theoretical talk. The data presented here exemplify how, in the beginning, students' talk is muddled revealing little resemblance to subsequent ways of describing phenomena in observational and theoretical terms. However, students engage in the world to manipulate and sense objects. These manipulations are associated with object movements that themselves lead to salience of specific features. This salience is a crucial, operative factor in ostensive definition of objects and events (Quine, 1995).

Second, gestures are not only about objects and events but also occur over these entities. Gestures serve to ground (link) particular expressions in particular material aspects (ostensive function). This ostensive function of gesture allows a spreading of communication across different modes of expression. Because of this connective function to language during the latter's initial emergence, it is crucial that students be given the opportunity to engage in attempts to describe and theorize phenomena in the presence of the original materials and

a detached human observer might call the same object. However, when these robots interact, one can note that some "groups," despite initial differences in the way they see and denote objects in their world, develop shared ways of seeing and denoting. It can also be observed that those "groups" of robots that develop shared ways of seeing and communicating have greater survival rates than those that do not develop shared ways.

equipment. As our examples from the German classroom illustrated, it is through a slow evolutionary process that students develop the competence to talk about the phenomena independent of their presence. In this respect, the patterns in the development of scientific language mimic those characteristic of early language development (Lock, 1997). That is, physical gestures become accompanied by vocal gestures (utterances) that, in the case of high school students, have conventional form through their prior experience. Furthermore, students' verbal and written expressions therefore become increasingly "abstract," that is, independent in their form from the original events that they describe. The transition moves from sensori-motor iconic to symbolic iconic, and from iconic to symbolic forms of signs. The ostensive function of gestures, which links emerging words and objects in the students' world, is a cultural invariant. Therefore, it provides the basis for new language to emerge, thanks to the shared environment in which students work. That is, through their interactions, and drawing on deictic and iconic gestures, students can come to agreements about just what is perceptually similar. These perceptually similar entities become the basis on which language can emerge. (See also footnote 3.)

We argue—grounded both in studies of language emergence among scientists and students—that writing and other formal ways of representing observational and theoretical descriptions should follow extensive opportunities for talking (and gesturing) science in the presence of the objects and events. Our initial results are consistent with theories of language emergence, particularly the integration of bodily movements, gestures, language, and other aspects of cognition (Bourdieu, 1997). As they enact their muddled talk and gestures, students make available to each other those entities that become salient to them, which, in turn, become the topic of their conversations. It is through their interaction that students can become aware of the extent to which their perceptions of the entities are shared. Sharing perceptions and the observational descriptions associated with them is not something that can be taken for granted; rather, there is evidence that students see phenomena in (sometimes radically) different ways (e.g., Roth et al., 1997b). However, out of the interactions, students can come to reliably associate verbal expressions, gestures, and objects and events—which, thereby, make a transition from idiosyncratic personal experience to shared aspects of the world.

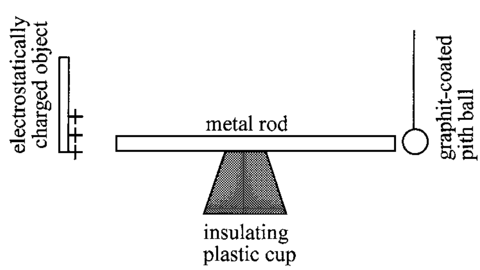
Gestures and language are also available to the teacher in the class. As such, she has many opportunities for identifying the entities that are salient to students, and how these are represented in talk. More so, Goldin-Meadows and her associates suggest that mismatches between gestures and talk can be used to make inferences about individual's current understandings (Goldin-Meadow, Wein, & Chang, 1992; Goldin-Meadow, Alibali, & Church, 1993). They suggest that during transitions, gestures precede verbal means in communicating the new understandings. Thus, teachers who pay attention to and read students' gestures can help facilitate (i.e., scaffold) the emergence of appropriate language because its precursors already exist in sensorimotor representations. In this respect, the role of the teacher is of particular importance, for there are no criteria available for selecting one way of talking over another before these ways actually exist (Rorty, 1989). Students (as scientists) have no way of judging the appropriateness of their ways of talking until some later point. Only from the vantage point of a consistently viable language is it possible to point out the problems arising from earlier forms of talk. Teachers, however, already know the observational and theoretical language that students are to learn. Through their interactions with students, and assisted by their reading of gestures, they can scaffold students in their development of new forms of (protoscientific) language outlined in the curriculum.

We consider the work sketched here only as a beginning, perhaps a hypothesis that raises many questions about the relationship between hands-on science activities and the emergence of language among students of different cultural origins. Because manipulating things in the world give rise to salient objects and events, students, even though they may speak different languages, can come to agree on what they see. In this process they are supported by their deictic and iconic gestures. In turn, these gestures provide a base on which common forms of verbally referring to, describing, and explaining can emerge. And finally, although there is a considerable literature in anthropology and psychology about the pervasiveness of gestures and their role in cognition, there exist only a very small number of gesture studies in education (for a comprehensive view see Roth, in press-c). We suggest that there is a need for studies that explore the role of gestures in, for example, science and mathematics learning. Once we know more about the role of gestures in scientific and mathematical cognition, we can then move to the next level and make recommendations how teachers might use this knowledge to inform their communicative actions and curriculum design.

APPENDIX: PITH BALL AND METAL ROD INVESTIGATION

Investigation and Observation

In this investigation, students first bring close and then remove a charged object to the metal rod. They can then observe the graphite-coated pith ball move toward and touch the metal rod. The pith ball then continues on its own to move to, touch, and bounce back from the metal rod. The bounces decrease until the pith ball returns to the starting position.



Scientific Explanation

Scientists explain the phenomenon in the following way: (1) As the charged object is brought to the metal rod it produces a charge separation; (2) A similar process occurs between the metal rod and the pith ball, with opposite charges facing each other. Although the pith ball is neutral over all, it is seen as charged from the direction of the metal rod; (3) Because oppositely charged objects attract each other, the pith ball is attracted to the metal rod where it takes up charges and becomes effectively charged; (4) The removal of the charged object leaves the metal rod charged in one sense and the pith ball in the opposite sense, thereby attracting each other, which leads to the movement of the pith ball; (5) Each time the pith ball touches the rod, some of the earlier "stolen" charges are given back until the electrostatic forces between the two objects are too small to allow the pith ball to touch the metal rod.

We thank Prof. Dr. Manuela Welzel for providing access to the data from her classroom. Also we thank the two anonymous reviewers whose critical comments and questions allowed us to improve the previous version of this paper.

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