Graphing: Cognitive Ability or Practice?

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Received 27 March 1995; revised 1 April 1996; accepted 1 May 1996

ABSTRACT: Traditional views conceive graphing as knowledge represented in students' minds. We show in our critique that such views lead to a common assessment problem of how to account for variations in performance across contexts and tasks, and a common attribution problem that locates difficulties in students' deficient cognitive apparatus. Grounded in recent research of scientists at work and everyday cognition, this article provides an alternative perspective that conceives of graphing as observable practices employed to achieve specific goals. This perspective highlights the nature of graphs as semiotic objects, rhetorical devices, and conscription devices. This shift in perspective dissolves problems with assessment and inappropriate attribution of student difficulties. The plausibility and fruitfulness of the new perspective is illustrated in three ways. First, we show that successes and failures of various graphing curricula become understandable in terms of the presence or absence of social dimensions of the practice. Second, we show how our perspective necessitates new assessment practices. Third, we show how our practice perspective on graphing led us to different learning environments and to new foci for conducting research in student-centered open-inquiry contexts. ©1997 John Wiley & Sons, Inc. *Sci Ed* **81**:91–106, 1997.

INTRODUCTION

> The consensual nature of mathematics is expressed and described mathematically; that is, it is available in the actions of doing intelligible mathematics. To say this does not imply that mathematicians' practices are given a complete and determinate representation by mathematical formulae but that no such representation can be constructed and none is missing. (Lynch, 1992, p. 230)

Our opening quote points out that any understanding of intelligible mathematical practice is

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CCC 0036-8326/97/010091-16

expressed and described by observable mathematical activity; and no description of mathematical practice can ever be complete. In contrast, many educational researchers seek mathematical understandings in individual students' heads rather than in their public activity of doing math (for a comprehensive review of the literature on graphing from a cognitive perspective see Leinhardt, Zaslavsky, & Stein, 1990). A recently published study from this perspective (Berg & Smith, 1994) highlights two major problems with this approach. The first problem relates to assessment. As Berg and Smith recognize—their study was designed to deal with this—cognitive ability cannot be read out directly; rather, students' responses are contingent on question format and context. Second, the cognitive abilities framework easily leads to the conclusion that some individuals have *innate* problems learning graphs: Many students "do not have the mental tools to engage in a high level construction or interpretation of graphs" (Berg & Smith, 1994, p. 549).

We consider both problems serious enough to warrant a different approach. Thus, graphing can be viewed from a different perspective, one that is informed by recent work in science studies. This perspective views graphing as practice; it focuses our attention on students' competence and rhetorical purposes, and on the affordances of graphs to collective sense-making. These new foci lead to instructional considerations that parallel those in other areas: to become a good public speaker, basketball player, or research scientist, one has to participate in the practice as speaker and listener, player and audience, researcher and critic. In the practice perspective, competence is observable, releasing researchers from constructing putative cognitive frameworks. Furthermore, the practice perspective focuses on participation in meaningful practice and experience; lack of competence is then explained in terms of experience and degree of participation rather than exclusively in terms of cognitive ability. The purpose of this article is to detail some of the problems with the cognitive ability view and to sketch an alternative perspective, graphing as practice, and its implications for assessment and curriculum design.

GRAPHING AS COGNITIVE ABILITY

> Unfortunately, many of our subjects do not have the mental tools to engage in a high level construction or interpretation of graphs. [A study] which investigated the connection between logical thinking abilities and the ability to construct and interpret graphs, indicates that subjects with deficient logical thinking abilities such as spatial thinking and proportional reasoning have significant difficulties when attempting to interpret or construct graphs. (Berg & Smith, 1994. pp. 549–550)

Many traditional studies in science education view graphing as a composite of individual cognitive abilities and skills, and view graphs as (mental) representations: Graphs "serve as representations of real observations and as analytic tools for detecting underlying patterns, which in turn inform the observer and the learner about the phenomena (the target) under investigation" (Leinhardt et al., 1990, p. 20). In this tradition, researchers focus on the objectifiable relationships among graphs, and between graphs and corresponding algebraic rules and situations. In their review of the literature on graphing, Leinhardt et al. direct our attention to three important "spaces" related to graphing: graphs; situations; and algebraic rules. Mathematics educators are, depending on the current curricular topic, interested in algebraic rules, graphs, and the movement within and between these spaces. Most science educators, however, are more interested in the relationship between graphs and situations and—mostly limited to older and advanced students—to the relation between algebraic rules (such as motion equations, optical equations) and situations. Hence, science education research on graphing focuses on three areas: students' interpretations of the concepts expressed in graphs; students' interpretation of graphs as pictures of situations; and students' problems with the scaling of graph axes. For example, Beichner (1990) claimed that students "fare poorly when asked to explain the concepts conveyed by the graphs" (p. 804); other studies focused on students' misconceptions—the "confusion" between height of a graph at a certain point and the slope at this point—or on students' mistaken interpretations of graphs as pictures (Berg & Smith, 1994); and Wavering (1989) claimed that students did "poorly" when asked to scale the axes of graphs. The reasons for these performances are often sought in terms of cognitive abilities or development.

Research in the Piagetian tradition frequently uses *students-as-concrete-thinker* or *student-lacking-logical-thinking-structures* as resources to explain failures to do graphing tasks according to researchers' standards (Berg & Philips, 1994; Wavering, 1989). A frequent claim in the literature maintains—often based on age-related differences in test results—that students' difficulties arise from "deficiencies" in logical reasoning ability. Several studies that surveyed students from grades 6 or 7 to grade 12 noted that the ability to graph is related to logical reasoning ability (Berg & Philips, 1994; Wavering, 1989). In one study that employed this kind of discourse, researchers inferred from their observations that students "quickly draw first reactions—often an undeliberate line, scribble, or points plotted without a pattern" (Berg & Smith, 1994, p. 548). Furthermore, scaling axes is said to require some form of abstract reasoning which begins to develop in students in grade 9 and above. Younger students and anyone else who is not a "formal thinker" cannot be expected to graph properly. If teachers (or researchers) take this perspective, they may easily blame deficiencies on students' cognitive abilities and end in a state of despair. As the quote opening this section suggests, they may conclude that students cannot graph because they "do not have the mental tools to engage in a high level construction" or have "deficient logical thinking abilities such as spatial thinking and proportional reasoning" (Berg & Smith, 1994, p. 549).

Thus, although it is generally recognized that graphing is not an important aspect of instruction and a "marginal, extra topic in most commonly used commercial textbooks for most of the elementary years" (Leinhardt et al., 1990, p. 3), research in this tradition focuses on what students *cannot* do. Students have little experience in graphing, yet they are expected to do it well.[1] Such descriptions conjure images of "fuzzy, approximate, and ungrounded beliefs" that contrast with the "precise, certain, and justified knowledge" of scientists, and teachers of science (Latour, 1987, p. 216). However, Latour (1987) warned against attributing such distinctions to cognitive abilities and differences in the respective rationalities. As an example, Latour described the encounter between native Chinese villagers and Lapérouse, a French captain and explorer. The differences between the two appeared to be "colossal": on the one hand, the implicit, local, approximate beliefs of the Chinese; on the other hand, the explicit, universal, precise knowledge of the French geographers and cartographers. It would be premature to attribute these phenomena to concrete versus abstract thinking (which Latour [1987] has called "first degree intuitions" and "second degree reflexion," p. 216): Differences in purpose and cultural resources and practices suffice to account for the differences between the Chinese locals and the French explorers. Similarly, differences in resources and practices can account for the differences in graphing competence between students and professional scientists.

[1]One of us (W.-M.R.) has done research in this same tradition. However, in returning to the classroom he found that such views are not helpful and rather unproductive in the daily concerns of science teachers. This essay, and the classroom research we have been doing since, grew out of these concerns.

Measuring Graphing Ability

When graphing is considered a cognitive skill, studies must be concerned with the design of instruments that most reliably measure this ability; that is, the problem is one of getting students to make marks on paper which can be said to stand in direct relationship with the hypothesized cognitive skill. For example, Berg and Smith (1994) designed their study to find out if there were differences between multiple choice questions and questions which allow students to draw and explain their own graphs. Indeed, they found statistically detectable differences in the distributions of graph types based on test format. From a situated cognition perspective, however, this is not surprising: the problems framed and solutions constructed are intricately tied to the available structuring resources and their salience to the individual. Ample research in the everyday use of mathematics shows that not only is test performance different when the contexts of testing are changed, but also (and because of the change in context) mathematical performance cannot be isolated as cognitive ability in people's heads (Lave, 1988; Scribner, 1986). Rather, "cognition" is situated such that the setting contributes to and constitutes an important structuring device for framing problems and constructing solutions. Tools available in a setting (which themselves are idiosyncratically constructed according to the prior experience of the problem solving individual) contribute to the form that any single solution takes.

For example, we found in our own research that an elementary teacher, although quite capable of doubling 1¾ cups of flour in a recipe (as she subsequently demonstrated), structured her work according to the setting. She used a 1-cup measuring device graded in ¼-cup increments and took first two 1-cup and then two ¾-cup measures of flour rather than multiplying the quantities to get a required 3.5 cups and measuring this out (McGinn, 1995). This woman did not have a defect because she did not multiply. Rather, in her solution, she not only used the required amount of flour, but she also demonstrated her intuitive understanding of the distributive properties of multiplication and the commutative properties of addition.

For similar reasons, we could have made a serious error in interpreting our data in the following situation. We asked 17 university science and mathematics graduates (who were in their fifth year to prepare for a teaching career) to solve a problem that we had earlier given to grade 8 students (Roth & Bowen, 1993). This problem presented a map subdivided into sections for which data were provided about the percentage of area covered by brambles and the average amount of light. Based on this information, students were asked to describe any patterns they saw in the data, make claims about what these patterns meant, and to justify those claims. Seven of 19 groups of grade 8 students used a canonical scientific approach and graphed; an additional 5 groups used other mathematical approaches as solutions. In contrast, only one university student used a graph, while the others said that a solution was impossible. We are far, however, from concluding inferior cognitive ability for the university students. Rather, the differences in common practices within the respective communities are more likely explanations. Our grade 8 students were accustomed to constructing mathematical re-presentations for rhetorical purposes, to convince their peers and teachers of the knowledge claims they made; they were also used to analyzing the mathematical re-presentations prepared by their peers. The university students, on the other hand, had a standard fare of science teaching. Applied to the testing of graphing from a cognitive perspective, it can be expected that solutions, especially with neophytes in the graphing practice, will be different if students see labeled graphs and sketches from which they choose, or if they have blank graphs with labeled axes to sketch their own graphs (cf. Berg & Smith, 1994).

Some studies have sought to eliminate the testing problem through interviewing, asserting that interviewees' responses are unaffected by the interviewer (e.g., Berg & Smith, 1994). However, the analysis of interviews by researchers with extensive experience in situated cognition and interaction analysis showed that even when the interviewer acts in the most dispassionate manner to "guarantee" the objectivity of responses, answers showed all signs of being socially constructed rather than pure measures of the interviewee's cognition; that is, interviewer and interviewee contributed to the form and content of responses (Suchman & Jordan, 1990). Accordingly, a considerable amount of research shows that cognitive performances are socially contextualized responses (for a review, see Perret-Clermont, 1993). Any assessment of interviewees' competencies is thus affected by social factors including climate of testing (cooperative or competitive), social dimensions of the situation (individual or public), and other characteristics (linguistic, motivational, and personal).

The problems with the cognitive ability view of graphing warrant the consideration of new perspectives. Here, the monograph *Science in Action: How to Follow Scientists and Engineers through Society* (Latour, 1987) provides considerable advice. Its *sixth rule of method* states that, when faced with attributions of differences to irrationality and naive beliefs, researchers should study in detail individuals, particularities of their settings, and their practices. Then, if anything remains unexplained, we may resort to cognitive ability as an explanatory resource. Following this suggestion, we now turn to graphing as practice.

GRAPHING AS PRACTICE

> Practice is our everyday practical activity. It is the human form of life. It precedes subject–object relations. Through practice, we produce the world, both the world of objects and our knowledge about this world. Practice is both action and reflection. But practice is also a social activity; it is produced in cooperation with others. To share practice is also to share an understanding of the world with others. (Ehn, 1992, p. 118)

The cognitive ability view of graphing misses a considerable number of issues that arise from the use of graphs in the everyday pursuit of goals. The notion of practice decenters the discussion of teaching and learning by focusing on observable features of members' activities in the process of accomplishing their goals. The difference between a cognitive ability and a practice perspective is exemplified by the difference between the meaning of signs (words, graphs, formulas) residing in someone's head and the situated use of signs as part of a community's everyday discursive practice (Brown, Collins, & Duguid, 1989; Edwards, 1993). Brown et al. discussed examples of vocabulary learning in which children used words, which they had learned from dictionaries, in inappropriate ways; they knew the definitions, but they had no conceptions how the language was used, how the words fit into the discursive practice as a whole. That is, knowledge acquired away from the context of its use is often piecemeal, brittle, and *use*less. On the other hand, Lave (1988, 1993) showed that practices are inseparably tied to members' goals and intentions. Outside schools, people use graphs to achieve certain ends: a newspaper editor may illuminate the message of an article by graphing the relationship between alcohol consumption and cholesterol levels; a physicist may enhance an article with a graph that underscores a claim about the signal-to-noise ratio of a new detector; or a science educator may use plots to highlight the different correlations between posttest scores and prior knowledge for different types of learners. In schools, however, students make graphs for the purpose of making graphs. That is, to paraphrase Bakhtin (1981), students have no opportunities to populate graphs with *their own* intentions. Educators and others often claim that individuals need to appropriate knowledge and skills before they can legitimately participate in a practice. However, many complex traditional practices such as tailoring or midwifery are appropriated as newcomers without prior knowledge legitimately but peripherally participate with more experienced members; through increasing participation and learning, the newcomers eventually become old-timers and core participants in the practice (Jordan, 1989; Lave & Wenger, 1991).

Everyday mathematical practices such as using numbers, graphing, scaling, or timing are inseparably submerged, tied up, and dispersed within a dense network of ordinary conversational activities (Lynch, 1991). Thus, “the knowing and learning of mathematics is situated in social and intellectual communities of practice, and for their knowing of mathematical knowing to be active and useful, individuals must learn to act and reason mathematically in the settings of their practice” (Greeno, 1988, p. 482). Consequently, “learning mathematics involves acquiring aspects of an intellectual practice, rather than just acquiring some information and skills” (p. 481). As the quotes heading the article and this section show, other authors agree. Participation in mathematical practices allows discursive and tool-related practices to be acquired through mutual observation, emulation, and correction in shared situations. In the process, any mathematical expression achieves meaning as part of observable practices and their circumstances because the consensual culture of mathematics is available only in the actions of doing intelligible mathematics (Lynch, 1992; Quine, 1987). That is, mathematical practices—such as graphing—take their meaning from the situation of their use in communities where members share many of the same assumptions, preconceptions, and common sense notions (Lave & Wenger, 1991).

Graphing is one of an array of signing practices such as talking, writing, gesturing, drawing, or acting used extensively in scientific communities (Lemke, in press). These practices are codeployed so that any single one can only be understood within the network of practices, that is, in its relationships to other practices. To do science, one has to be able to juggle and combine the various practices that are codeployed to make scientific “concepts.” These practices relate to natural phenomena not because of some logical necessity but because they are associated with the conventions established in each field (Latour, 1993). In scientific and engineering communities, graphs have three major purposes: graphs are semiotic objects that constitute and re-present (and reify) other aspects of reality; graphs serve a rhetorical function in scientific communication; and graphs act as conscription devices that mediate collective scientific activities (talking, constructing facts). In the following three sections, we focus on each of these aspects by weaving together findings from science studies and our own work.

Graphs as Semiotic Objects

An important point seldom addressed in science education literature is the relationship between a graph and the reality it constitutes (Leinhardt et al.’s “situations”). In a frequently used test question, students are required to imagine walking across the room, and then are given a choice between various graphs, or are asked to draw a graph, re-presenting the imagined walk (Berg & Smith, 1994; Mokros & Tinker, 1987). Here, researchers assume a simple relationship that can be expressed as {physical experience of, or imagined, walk $\leftrightarrow$ graph} which expresses an isomorphism (or re-presentation). The relationship is bidirectional, because it is assumed that a literate person can read specifics of the walk from the graph, or construct a graph after making (or imagining) a walk. However, there is evidence that this relationship has to be constructed in the same way as the relationship between the word “cat” and some furry creature that meows. Recent studies in philosophy, history of science, and ethnomethodology have shown that the graph, like the word, is an independent semiotic object whose relation to the phenomenon has to be established through considerable work; the relationship holds because of convention, not because of an a priori ontological connection (Gooding, 1992; Latour, 1993; Lynch, 1991; Rorty, 1989). In this work, semiotic objects, perceived phenomena, and available tools (technical, linguistic) change and are mutually adjusted until they can be regarded as isomorphic.

In a study of physics lectures, we have shown the complexity of the process that translated a simple phenomenon (a ball rolling down an inclined plane) into different sets of tables and graphs, and ultimately sets of sketches which (for the presenting university professor at least) stood for other more cumbersome verbal and mathematical descriptions of motion (Roth & Tobin, 1996). Thus, rather than assuming a simple mapping of a walk across the room onto a graph, it would be more appropriate to study the translations, transformations, and transpositions required to construct the relationship between the event and its re-presentation.

We are not claiming that graphing is a simple practice. Rather, for novices it is quite difficult to decide if a signal is a sign (semiotic object) that points to an "interesting" phenomenon or is merely an artifact. Thus, whether the sequence $\{(x, y)\ (1, 6.0)\ (2, 6.1), (3, 6.2), (4, 6.3)\}$, which can be represented by an x–y line graph, represents a phenomenon of interest or an artifact is a matter of context. When plotted with the abscissa scaled from 0 to 7, there is hardly anything to see. If the abscissa is scaled from 6 to 6.5, a steeper curve results. For the experienced person, the choice of axes is driven by theoretical considerations. But even scientists do not easily separate signal from noise. For example, astronomers had studied photographs and put them aside as uninteresting. Later, after the first Galilean pulsar was "discovered," they studied their photographs again. What they had first read as blotches, suddenly turned into "good" signals supporting the existence of other pulsars (Garfinkel, Lynch, & Livingston, 1981). The difficult work of reading signals becomes especially clear during controversies that are eventually declared as hoaxes (Schnabel, 1994). Thus, serious scientists had supported N-rays and cold fusion until someone else constructed the phenomena as artifacts: they turned good signals into blotches and wiggles. This issue is not a trivial matter, but part of the daily work of scientists, politicians, and economists.

Researchers sometimes relate graphing to Piaget's cognitive developmental levels and formal reasoning (Berg & Philips, 1994; Berg & Smith, 1994; Wavering, 1989). Rather than building on the associated traditional notions of concrete and abstract, we focus on the nature of mathematical re-presentations on a continuum from experience-near to experience-distant. Thus, the notes and sketches students produce in their field site during a study of ecology, and the samples they bring back to the lab for analysis are experience-near re-presentations of the original field site. When they transform and summarize this information into lists and tables, they produce re-presentations that are more removed from the field site; but these re-presentations exhibit information that reveals the original field experience much more closely than later transformations of their idea into averages, graphs, and equations on which students base their knowledge claims, and with which they convince peers and teachers that these knowledge claims are founded (Roth & Bowen, 1994). Whether a person is competent in a complex practice such as graphing, and uses graphs deliberately and with ease as re-presentational and rhetorical devices is a function of experience in producing more and more experience-distant re-presentations rather than just cognitive development (Latour, 1987; Roth, 1995; Wilenski, 1991). We showed that students can become competent in moving from natural objects and events to increasingly complex re-presentations using a cascade of representational devices that are more and more experience-distant; and equivalently, they can become experienced in making the reverse trajectory, from experience-distant graphs to real or possible natural objects and events, a process usually referred to as interpretation (Roth, in press; Roth & Bowen, 1994).

Graphing as Rhetorical Practice

Science studies research has shown repeatedly how scientists use graphs as rhetorical devices which, in conjunction with texts, elaborate these texts (Bastide, 1990; Lynch, 1990; Star & Griesemer, 1989). Graphs are used to highlight certain features of researchers' construc-

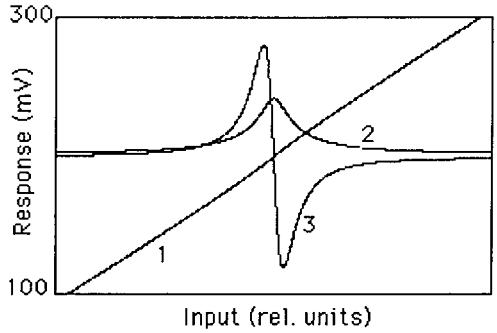

Figure 1. An example of the processes by means of which physicists construct a "clear" signal from an otherwise unseaming signal (1). By constructing first (2) and second derivatives (3), minute variations can be amplified and constructed into "facts." This simulation was constructed from data points that follow the function $f(x) = x + 0.05 \cdot \mathrm{asinh}(5x)$.

tions about nature.[2] In the process, researchers use a variety of processes to make these features stand out, and to eliminate others that could be distracting. Geneticists cut and paste audioradiographs used in the "identification" of certain DNA sequences to obtain graphical re-presentations on which DNA sequences are distributed along the y-axis, and various samples constitute the categorical x-axis (Amann & Knorr-Cetina, 1988; Knorr-Cetina & Amann, 1990). Physicists frequently use the mathematical practices of integration (or spline functions) to turn sequences of data points into smooth graphs and give them a more familiar look, or use differentiation to obtain a dominant peak where data show a continuous and smooth function. How one can coax a clear "fact" from a seemingly straight-line signal is simulated in Figure 1. By manipulating the original electronic response (1) in a way that corresponds to mathematical differentiation, new signals (2, 3) can be constructed which appear to point to a clear signal from a phenomenon.

Change of scale, change relative to some reference value, and the spatial representation of time are some other techniques employed to construct phenomena through graphical representations (Bastide, 1990). Wainer (1992) illustrated an interesting example of how a journalist's claim that was supported by a graph could be inverted. The original claim that student achievement remained constant over a 10-year period despite increasing education expenditures was supported by a double-y-axis graph. By manipulating the scales for both y-axes separately, Wainer created a graph suggesting that student achievement gains "soared" while education expenditures remained stable; a simple change of scale supported opposite interpretations. What is almost never made clear in science education (teaching or research) is that much of scientists' work is constituted by differentiating blotches and wiggles into just that and "real signals" (Woolgar, 1990). Here we can see the close relationship between graphs as a means to constitute a phenomenon (the scientific experimental manipulations that culminate in a graph through which the phenomenon comes to life), and graphs as clear and unmediated evidence of a phenomenon that enters everyday discourse as "fact."

The purpose of manipulations is to help others with less or no experience see what a researcher has seen. But in these manipulations, phenomena are constructed which otherwise do not exist; these graphs not only bring out phenomena, being constituted in and through scientists' descriptive work, but are used as evidence for the phenomena (Latour, 1990; Woolgar,

[2]Lemke (in press) illustrates that scientists go even further than this. They even use graphs in footnotes not only to elaborate text but to explain other graphs.

1990). The precarious relationship between phenomena of the physical world and the representational practices of science has been repeatedly pointed out, and described as a sequence of *translations* and *evidence-fixations* (Amann & Knorr-Cetina, 1988; Latour, 1987, 1993). With respect to science education, we have been able to observe and describe multiple translations, evidence fixations, and suppressions of unwanted deviations in the teaching of college level physics for preservice elementary teachers (Roth & Tobin, 1996). In this course, the professor's intent was to enroll his students in viewing the world from a Galilean–Newtonian framework. From the original staged phenomenon, a ball rolling down an inclined plane, the professor generated a series of tables and graphs that were supposed to teach an understanding of motion phenomena. What the professor had not considered was that his students were not competent in the mathematical practices of translating data tables into each other and into graphs. For the professor, there was a clear and unmistakable link between the phenomenon and the graphs, whereas there was a big gap and a meaningless correspondence for the students.

The question here is not one of accuracy or truth of graphs. Some researchers presume that people simply have to "accurately interpret graphs and to detect false use of graphs" (Berg & Smith, 1994, p. 529). However, graphs can be transformed in legitimate ways (as determined by the community) to emphasize various aspects. Our concerns are whether graphs in their original or transformed appearance support a claim in a convincing manner. Teachers can then respond to traditional student questions such as "How do I do the graph?" with "What do you want the graph to show?" Such a change in educational practice is in line with Lave's (1988, 1993) recognition of the inseparable link between practices and intentions. Depending on the students' current competence, the teacher may decide to provide support on a need-to-know and just-in-time fashion to help the students reach their goals (Roth & Bowen, 1995).

Graphs as Conscription Devices

As a central aspect of a practice, graphs have another function besides being inscriptions (semiotic objects) that are used for rhetorical purposes: As conscription devices, graphs bring together and engage collectivities[3] to construct and interpret them (Garfinkel et al., 1981; Roth & Bowen, 1995; Woolgar, 1990). As conscription devices, graphs coordinate sustained interactions in the same sense that other visual re-presentations enlist the participation of those who employ them in the laboratory or in scientific publications, since users must engage in generating, editing, and correcting graphs during their construction. Here, graphs are central to interactions among scientists. Graphs constitute a shared interactional space that facilitates communication because of their calibrating effect on what can be taken as shared, and what has to be negotiated when it becomes obvious that it cannot be taken as shared. Thus, graphs are not only tasks to be accomplished through talk, but they also make talk meaningful. In this, talk and graphs are in a reflexive relationship such that one draws on the other to be meaningful.

At various points we have provided analyses of students' collective sense-making activities over and about graphs (Roth, 1995, in press; Roth & Bowen, 1994, 1995). These analyses show that graphs are not only the objects of students' talk, but also provide students with additional communicative resources. Students point directly to data points, lines, and axes; use

[3]Because groups that work on a common task can use collaborative or adversarial strategies to construct the meaning of an inscription, we prefer the notion of collective. This expresses that the task is accomplished by more than one person, but leaves open for more detailed description whether it is accomplished through adversarial or collaborative strategies (Pea, 1994).

gestures to indicate trends; or invent indexical labels to describe aspects of the graph (e.g., "question mark graph" to distinguish a graph resembling the curved shape of a question mark from a straight line graph). The physical presence of the graph also supports the topical cohesion of the emerging conversation. There are suggestions that this social aspect of using graphs and other diagrams will lead to increased competence in the "authentic" ways of doing and talking science (Pea, Sipusic, & Allen, in press; Roschelle, 1990; Roth & Bowen, 1994). Through their interactions over and about graphing tasks, students become competent users of graphing practices. This competence has a double nature in that students become proficient in using graphs to constitute and re-present phenomena of their interest, but also to understand the relevance of graphing. Students no longer see graphs as unequivocal representations, but see graphing as a goal-dependent practice of re-presenting (Roth, in press).

IMPLICATIONS FOR SCIENCE EDUCATION

> In order to describe and understand, as well as to theorize learning in small groups, detailed analyses of actual classroom learning have to be conducted. The settings need to provide stable contexts for students in which they become increasingly knowledgeable. Long-term, fine-grained collection of data sources can and will provide the data which we will need to construct viable theories about interactions and learning in small groups. (Roth & Bowen, 1995, p. 125)

New perspectives, like new theories, should not only be plausible and intelligible but fruitful in that they suggest new ways of designing instruction and new research questions. What does our change in perspective afford to science educators? If graphing is seen as one of many practices in constructing and re-presenting phenomena, instruction changes in a variety of ways. Implicit understandings of practice are developed in practice; practices are appropriated as newcomers participate in them with their peers and with old-timers (Bourdieu & Wacquant, 1992; Brown & Duguid, 1992; Lave, 1993). Thus, if students are to develop graphing competence, they need to participate actively in the development and maintenance of this practice. Graphing then becomes a collective activity during which phenomena are constructed; students focus on making inscriptions increasingly convincing. Rather than being an abstract ability attainable only by a few gifted students, graphing becomes a shared social practice paralleling many others, in which one is more or less competent, which in part is a function of the extent of experience. In the collective activity, teachers are more experienced others, old-timers, who may decide to model canonical practices. Once graphs are part of students' everyday communicative practice, they become increasingly palpable objects rather than remaining experience-distant (abstract) and meaningless displays. When graphs are produced in collective efforts, they facilitate students' communication by providing a backdrop to their talk and gestures; they are outcomes of joint labor and indices for their shared understandings. As an authentic practice (scientists do it every day), graphing is an important aspect of communication; when used in classrooms, it can lead to student-centered science talk as recommended by Lemke (1990). In classrooms, as in scientists' laboratories, graphs can be tools for constructing facts and for mediating, in a reflexive relationship, the interactions during which facts are constructed. Using this practice perspective, we now take another look at students' "difficulties."

Students' "Difficulties" from a Practice Perspective

The problem of the cognitive perspective lies in its concept of a graph as something that exists in itself and has more or less unambiguous meanings. From this perspective, one immediately focuses on students' errors. On the other hand, if graphing—making and interpreting graphs—is but one of a range of discursive practices, we begin to focus on students' experience and use of graphing. Much like in second language learning, we would expect those students with few opportunities to engage in graphing as practice to show less competence than those to whom it is a routine way of talking science. But studies from a cognitive abilities perspective ask students to make inferences in a domain where they have few prior opportunities to engage in the practice. (Leinhardt et al. [1990] noted this lacunae but did not link it to student difficulties.) It is not astonishing that students come to conclusions that are at odds with current scientific practice. Such inferences are a familiar phenomenon in learning a language (another practice). For example, most parents notice that children (who learn English as their mother tongue) at some point in their development inappropriately generalize the "ed" ending in the construction of the imperfect tense: They may say "teached" instead of "taught." Furthermore, those readers who have acquired proficiency in a second or third language, will find striking similarities between the iconic confusion of graphs and phenomena, and language learners' confusion of literal and metaphoric meanings. In both cases, it would be premature to assume cognitive deficiencies. While it is clear that, in language learning, increasing communicative competence is associated with increasing participation in linguistic practices, similar associations have yet to be made to the appropriation of mathematical and scientific practices.

Our practice perspective throws new light on the success of microcomputer-based laboratory (MBL) instruction (Linn, Layman, & Nachmias, 1987; Mokros & Tinker, 1987; Nachmias & Linn, 1987). The benefits of MBL instruction to students' competence in graphing may not come so much because it changes individual cognition but because the MBL materials make "graphs [the] central means of communication" (Mokros & Tinker, 1987, p. 369). In these studies, students engaged in graphing-related practices for extended periods of time and across many activities (20 activities in the Mokros and Tinker study; 54 activities over an 18-week period in the Nachmias and Linn study). Furthermore, students used graphs both as objects to be talked about and as structural resources in communication. That is, in these studies, graphs also served as conscription devices. Not surprisingly, from our perspective, the children in these studies showed significant changes in their competence to talk about and use graphs.

Assessment Practices

Traditional perspectives tend to see students' competence in a negative form. Throughout Leinhardt et al.'s review one can read about "students' difficulties" (p. 22), "iconic confusions" (p. 22), "misconceptions" (p. 30), "misunderstandings" (p. 30), and "limited conceptions" (p. 31).[4] Such descriptions become meaningless in different perspectives on learning that replace traditional views of knowing and learning with the notion of participation in practice (Lave, 1993; Lave & Wenger, 1991). Here, individuals are not evaluated on the basis of what they can or cannot do, but on the extent to which they participate in specific practices as described by their status along a trajectory from legitimate peripheral to core participation. Language is a familiar practice, and language learning a suitable example to make an analogy. Rather than dwelling on "misunderstandings," more competent speakers usually assist newcomers by modeling accepted practices. While we have observed such learning with parents

[4]Ethnomethodologists suggest that the practices which lead to such labels are as much or more interesting than the phenomena they describe (Garfinkel, 1967; Mehan, 1993).

and their children, or in French immersion classrooms,[5] similar situations seldom exist for communicative practices in science, including graphing, talking, and writing (Lemke, 1990). (We present an exception from our own teaching below.)

From a cognitive ability perspective, researchers assume that students should be able to make inferences about graphs (considered to be objects with unequivocal inherent meanings). Our practice perspective permits educators to avoid a number of problems arising from unreasonable assumptions. No one would ask a person with 1 or 2 weeks of instruction per year in a foreign language to make "correct" inferences about complex linguistic relationships, about double entendres, etc. The practice perspective suggests a focus on developing competence in graphing as one of many practices that can be used to mathematize experiences for rhetorical purposes. Rather than assessing graphing abilities, science educators then evaluate students' competence in making convincing arguments about phenomena with which they are reasonably familiar. From our perspective, the assessment problem is to determine the extent to which graphs are used as part of rhetorical practices (means) in the pursuit of meaningful activities (goals) situated in and legitimated by knowledge communities.

Learning Environments for Participation in Graphing Practices

For researchers in science education, there are important unanswered questions with respect to graphing. What are the processes by means of which the isomorphism between natural phenomena and their corresponding graphs are constructed?; What trajectories do students take from their initial attempts as neophytes to become successful members in a community of graphing practice?; To what extent does competence in constructing graphs help students in interpreting/deconstructing the graphs produced by others? The following vignette illustrates a learning environment and the research that we designed based on the outlined view of graphing (and other purported "skills") as practice:

> Jamie and Miles are students in a grade 8 class engaged in a 10-week investigation of biomes. Like their peers, the two have staked out a 35-m^2 plot (ecozone) in a wooded area of the school grounds that constitutes their research site. For this first investigation, they have decided to check their hunch that the distribution of plants is related to soil differences. Jamie and Miles know that they have to make a convincing case for whatever finding they come up with.
>
> In the field, they select three sampling locations with clearly different plant coverage. They sketch a map of the physical layout, and mark the three sampling sites and the plants growing in each. They note a few other observations such as air temperature, cloud coverage, and amount of light on their ecozone. They take soil samples, but realize that just by looking at them, it is difficult to assess similarities or differences in a way that would be convincing enough when they present results to their peers. They take the soil samples and return to the lab. Here, they consult some of the resource materials, and then settle on a sedimentation test that can be used to turn a sample, by means of floating, into a stratified sediment with layers of different composites. They draw side views to scale, but find these not convincing enough as evidence for a later "sharing" session. Based on information from their resource materials, they decide to calculate the relative amount (in percent) of each strata in the three samples. They plot this information on a chart which they overlay with a published grid on classifying

[5]In Canada, where English and French are both official languages, English-speaking students can opt to enroll in French immersion programs. Here, all of their instruction is in French (with the exception of English literature, spelling, reading). They learn their second language by participating in its daily use.

materials according to the distribution of composite materials. The three samples clearly fall into different regions of the grid, which Jamie and Miles use to support their claim (made in their field report and during discussions with other teams) that, in their site, different plant coverage is associated with differences in soil type.

From a teaching perspective, graphing was embedded in Miles and Jamie's overall effort to convince others that differences in soil composition may be related to differences in plant coverage. Our study showed that at the beginning of the school year, neither Miles nor Jamie used graphs in support of their knowledge claims. Now, in the sixth week of the unit, graphing was the culminating activity in a series of translations by means of which they constructed their argument (taking ground, floating it, drawing the sediments, calculating proportions, plotting data points). Here, the students actively engaged in these transformations and reflected on them—for these students, practice was action and reflection. Spurred in part by the teacher's preference for replicable investigations which require standards across sites and time, and in part by the difficulties of comparing results in their discussion with groups who studied different sites, Jamie, Miles, and their peers mathematized their field experience to increasing degrees (Roth & Bowen, 1994). They found graphing as one of their more powerful rhetorical practices: "When [the teacher] said, 'How can you prove it,' we came up with the idea of the graph."

Another example that illustrates our focus on practice comes from a physics class. Students conducted optical experiments to find out if there was a relationship between distance of an object to a lens and the distance of the image to the same lens. In part, we used the activity to generate discussions among the students about the underdetermination of "laws" when they are derived (induced) from data. Figure 2 shows the original data and the polynomial of degree 4 generated by one student pair (curved line represented by a function of the type $f(x) = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4$). The goodness-of-fit index showed almost perfect fit ($R^2 = 0.9997$). Other students had proposed different relationships. During the whole-class conversation, the teacher proposed the second plot (top scale, straight line) using an inverse function

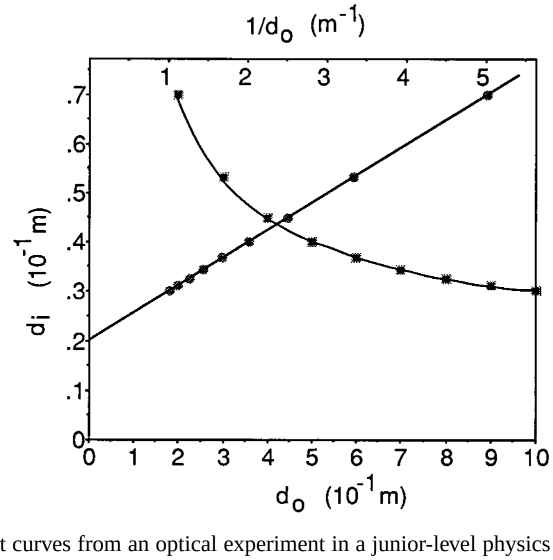

Figure 2. Data and best-fit curves from an optical experiment in a junior-level physics class. The two curves fit the data equally well. The decision to choose an inverse relationship over a polynomial of degree 4 has to be made in accord with social conventions and theoretical or aesthetic grounds.

with nearly the same goodness-of-fit index.[6] This gave rise to discussions of scientists' distinct practices of explaining experimental data by means of theory- and data-driven methods.[7] This situation provided an occasion to talk about the tenuous relationship between a particular set of data (or their plots) and a function, for there are several functions that provide equally good fits to the data. The decision of which function to use had to be made on other grounds such as parsimony, internal consistency of the domain, or fit with the theory. As with other "cognitive" values, the origins of intellectual, powerful, and preferred solutions lie in social practices rather than in individual minds (Wertsch & Rupert, 1993). Such decisions are based on conventions, not on sets of absolute criteria. Thus, rather than dwelling on "correct" methods of graphing the results from the optical experiments, we chose the situation as an occasion to discuss scientists' purpose and the relationships between data and theory. What we talked about, then, were scientific practices of achieving consensus, resolving disputes, and offering evidence.

Open Questions

Before closing we want to point out that our practice perspective also gives rise to new research questions. Thus, we are not simply interested whether students like Jamie and Miles or the physics students have the ability to plot their data points and find trends (in fact, they developed an increasing competence in doing just that). Rather, we are interested to find out how students transform lumps of soil, observations of plants, or sensations of temperature into various semiotic expressions that they use as evidence for scientific phenomena. Jamie and Miles participated in a classroom culture in which the construction of mathematical representations (such as graphs) and the rhetorical quality of their evidence were valued. Further questions a researcher might ask in this case are: How does the classroom community support the spreading and wide acceptance of a new practice (such as graphing?); How is cognition transformed with the adoption of new practices at the classroom level?; What are the processes by means of which students interpret graphs produced by other students and construct meaningful understandings of their peers' research?

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[6]To mathematical physicists, such a fit is not surprising for they are aware that any function can be developed in terms of a Taylor series yielding a polynomial. Thus, data that follow functions such as $f(x) = \sin(x)$ or $\mathrm{f}(x) = 1/x$ can be described to any degree of accuracy by choosing an appropriate polynomial of sufficient degree.

[7]It is interesting to note that scientists are not always interested in finding one analytical solution to their fit. One of us (W.-M.R.) worked as a physicist in a laboratory where spectra were described by means of spline functions; that is, series of different polynomials that changed from one interval to the next. The sole purpose of the spline functions was to provide a way of plotting smooth curves to stand in for the raw data.

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