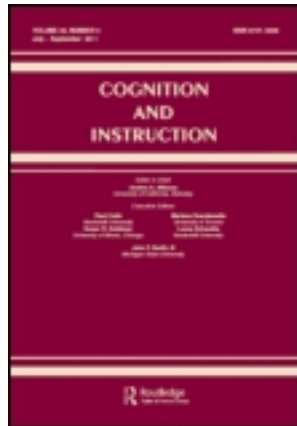


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Discovery Learning and Discovery Teaching

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Teachers interested in promoting student inquiry often feel a tension between that agenda and the more traditional agenda of “covering the content.” Efforts in education reform devote substantial time to addressing this tension, primarily through curriculum reform, paring the traditional content and adopting inquiry-oriented methods. *Discovery learning* approaches, in particular, are designed to engage students in inquiry through which, guided by the teacher and materials, they “discover” the intended content. Still, the tension remains, for example, in moments when students make discoveries other than as intended.

How teachers experience and negotiate these moments depends largely on their expectations of curriculum and instruction. For some, successful instruction entails progress through a planned set of observations and ideas, and such moments of divergence may represent impediments. Others see the classroom as an arena, not only for student exploration but also for teacher exploration, of the students’ understanding and reasoning, of the subject matter, of what constitutes progress toward expertise and how to facilitate that progress. For them, successful instruction depends on teachers’ often unanticipated perceptions and insights. One might call this *discovery teaching*.

This article presents a detailed account of a week of learning and instruction from my high school physics course to provide a context for discussion of the role and demands of teacher inquiry. For the view supported here, the coordination of student inquiry and traditional content is not simply a matter of reducing the latter and welcoming the former. It is a matter of discerning and responding to students’ particular strengths and needs.

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A MOMENT FROM A PHYSICS CLASS

Jean, Greg, Jack, and Julie¹ are at a lab bench in a high school physics class, working on Section 4.2 of *Electrostatics Activities for Students* (Morse, 1991).² Following the instructions, they have built the device shown in Figure 1, with two plastic straws attached to an aluminum pie plate, one straw wrapped in aluminum foil. They have called me, their teacher, to their lab bench to explain what they have found: If they put a charge on the plate, the foil-covered straw also becomes charged, but the plastic straw does not. Jean asks Greg to tell me his idea for why this happens.

Greg: Because this [indicates the plate] is aluminum, right? And this [the foil-covered straw] is the same thing, and we've already proved that this [the plate] is charged.

Teacher: OK.

Greg: And if it's the same material, and it's touching, that whole thing should be charged, too.

Teacher: Do you think if this [the plate] were plastic, then this [the plastic straw] would be charged?

Greg: If this [the plate] was proved charged, and it was plastic.

Teacher: So your idea is that, once any given kind of material, like if it's plastic, everything that's plastic that's touching it will be charged.

Greg agrees, and I check with Jean, Julie, and Jack, asking each in turn, "What do you think of that?" Julie nods "yes," and Jack says "It sounds good." Jean is hesitant, saying that "It sounds all right," but she wants to try an experiment.

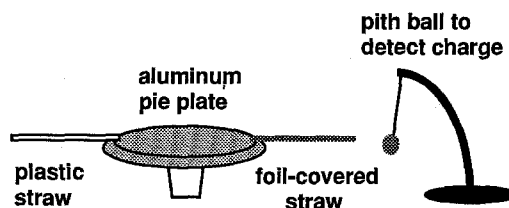
Jean: I don't know, could we, try it with the foam [Styrofoam™]? ... Charge a foam plate, and then put a foam cup on it.

I tell them "That's a great experiment," expecting it will disconfirm Greg's explanation: Styrofoam™ does not conduct electricity, so there will be no sharing of charge between the plate and the cup. To help ensure that outcome, I caution them to be sure the cup is not charged beforehand, and I move on to other students. Later, I ask them what became of their same material idea, and I am taken aback. Jack answers that they "found out it worked": The charge on the foam plate did spread to the foam cup. In fact, Julie says, they "tried it with another one. We put a [foam] plate on top of another [foam] plate," and it gave the same result—that charge moves from foam to foam just as it does from aluminum to aluminum.

¹Student names are pseudonyms.

²See Appendix A, Section 4.2.

FIGURE 1 Device for experiment in Section 4.2. An aluminum pie plate rests on a Styrofoam™ cup, with two straws attached.



A TENSION AMONG OBJECTIVES

For science educators interested in the broader aims of reform, there is often tension between progressive objectives of engaging students in their own “scientific inquiry” and traditional objectives of “covering the content.” On one side are intents that students learn to conduct their own investigations and to make their own observations—to invent, articulate, and defend their own explanations. On the other side are requirements that they develop an understanding consistent with a particular body of knowledge—that they arrive at scientists’ explanations for the phenomena scientists observe.

For a teacher in the classroom, the tension appears in moments such as this. With respect to their participation in scientific inquiry, the students in this excerpt have done as one might hope: Greg invented an explanation, Jean designed an experiment to test it, and, after replicating the results, the students formed their own conclusion. But Greg’s idea, that charge will spread to objects of the same material, is incorrect: Some materials, including aluminum, conduct electricity, and others, such as the foam of the students’ plates and cups, do not. Jean’s idea for an experiment seemed sound, but they must have done something wrong because what they observed cannot occur.

Among researchers and teachers, discussions about such moments inevitably elicit a similar split of concerns. Watching the videotape, some worry that I was allowing the students to mislead themselves, at the risk of producing or reinforcing misconceptions; others worry that I communicated dissatisfaction with their explanation, at the risk of discouraging their participation. Some praise both the students’ work as experimentalists and my having encouraged them to pursue their own ideas. Others criticize that the activity was inauthentic as science and as student inquiry, citing a tacit understanding that the appropriate observations and explanations were predetermined.

It is generally difficult to engage in any conversation about science education, whether with teachers, administrators, or curriculum developers, without encountering some form of this tension, couched in various terms including *process* and *content* (or *product*), *depth* and *breadth*, and *reasoning* and *answers*. The conceptualizations vary somewhat in purpose and in epistemological, psychological, or

sociological commitments; in general, they are framed in terms of a distinction between different aspects of knowledge and reasoning in students or scientists.

In this article, I draw a distinction between teachers' perceptions and intentions, specifically between those of *traditional content* and those of *inquiry* (Hammer, 1995b). The former pertain to what is traditionally seen as the content of the course: the established, intended body of knowledge. It is a traditional content-oriented perception, for example, that the same material explanation is incorrect, and a traditional content-oriented intention that students understand that electric charge moves in some materials (conductors) but not in others (insulators). Inquiry pertains to the nature and quality of students' participation in exploration, invention, and discourse. It is an inquiry-oriented perception that the students invented their own explanation and experiment, and an inquiry-oriented intention that they understand this as valid and valuable participation.

To emphasize, this is not a distinction between the content of students' knowledge and the processes by which they reason; it is a distinction between different aspects of teachers' perceptions and intentions. In choosing the terms to describe this distinction, I modify *content* with *traditional* and avoid the term *process*, because I do not want to adopt either the notion that traditional content is appropriately considered as the content (or substance) of a physics course or the notion that content and process are psychologically or epistemologically distinct.

For the purposes of this article, I adopt this description of the instructional tension, which I suggest is both genuine and legitimate: It is legitimate for me to want students to understand that some materials conduct electricity and others do not; it is also legitimate for me to want students to explore phenomena, design experiments, and invent their own explanations. Ultimately, I know, these two agendas should not conflict; they are both aspects of the same overall goal that the students develop scientific understanding. But what I hope will happen ultimately is of little help in this moment, as I try to decide how to respond.

DISCOVERY LEARNING

Efforts to reform science education, from the level of national projects to individual classrooms, devote substantial time and effort to addressing this tension. The idea that "less is more" motivates paring traditional content-oriented objectives; various frameworks, such as the lists of "abilities necessary to do scientific inquiry" in the National Science Education Standards (National Research Council [NRC], 1996), promote and organize inquiry-oriented objectives. Within the classroom, the coordination of traditional content and inquiry plays out in a variety of ways, from relatively minor adjustments of traditional methods to wholesale restructuring.

Some approaches entail designating particular activities as inquiry oriented, with traditional content—often seen as prerequisite to student inquiry—covered by traditional means. Thus, a teacher may lecture and assign problems to cover the

content and then address inquiry-oriented objectives through assignments that require students to apply what they have learned. Alternatively, the teacher may promote student inquiry through various forms of student projects (Ruopp, Gal, Drayton, & Pfister, 1993), including design competitions (e.g., to build the strongest bridge or tallest tower out of a given set of materials) and school science fairs, in which, in principle, students formulate their own questions and design, conduct, and present their own experiments. These projects may be conceptually tangential or distinct from the traditional content of the course, and teachers may assign them with few expectations of progress with respect to that content. For teachers following such methods, the tension between inquiry and traditional content plays out mainly in decisions about the use of time: how much to devote to inquiry-oriented activities, at the expense of coverage?

Other approaches integrate traditional content and inquiry-oriented agendas. Like all popular terms in education, *discovery learning* has taken on a range of meanings, but most often it refers to a form of curriculum in which students are exposed to particular questions and experiences in such a way that they “discover” for themselves the intended concepts. The student’s inquiry is usually “guided” by the teacher and the materials, such as through “Socratic” questions, because no one expects them to arrive on their own at ideas it took scientists centuries to develop.

In a discovery learning approach, the tension between inquiry and traditional content remains, but it takes a different form. The issue is no longer how to distribute the time between primarily inquiry-oriented objectives and traditional content-oriented activities but rather how quickly to expect or press students to progress through the discoveries. And what if the students do not discover what they are intended to discover? How forcefully and by what methods should the teacher guide them to the appropriate discoveries?

In the earlier excerpt, Greg, Jean, Julie, and Jack have discovered something that I know to be false, using methods of inquiry that I ought to support. And so, in this moment, I am torn. I could help them design and perform their experiment “more carefully,” so that it shows the correct answer. Perhaps they will come to accept that aluminum conducts and foam does not, but perhaps they will have less of a sense of their own access to physical phenomena, independent of my authority.

Some might suggest it was an error to encourage them to veer from the carefully designed, prescribed activities. But students still make unintended observations and inferences: During the same period, another group of students are following the directions in Section 4.2, and to my surprise and confusion, their plastic straw seems to be conducting electricity.

Others would argue that the students’ observations are clouded by their preconceptions, and they should learn to be more objective. But one could make a very similar claim about my reasoning: I disbelieve the students’ evidence in favor of what I know to be correct. I can invent an explanation for what they have seen, but my explanation is just that, an invention designed to be consistent with my

preconceived notions. Perhaps it is not entirely true that I want them to be more objective. It seems as though part of my inquiry-oriented agenda is that they learn to be appropriately prejudiced in conducting their experiments. In this moment, in this way, the tension between my traditional content and inquiry-oriented objectives is an intellectual chicken-and-egg: If they do not in some sense already know what will happen, they may not design their experiments well enough to see it.

INHERENT UNCERTAINTY

That students may discover, through legitimate inquiry, the “wrong” ideas, is now a familiar matter of epistemology. Educational psychologists (e.g., Hodson, 1988) and historians and philosophers of science (e.g., Feyerabend, 1988) argue that scientific truths are constructed, that they do not reside in the world simply to be discovered by those who look carefully.³ There are educational implications both with respect to objectives, that students should develop appropriate beliefs about the nature of science, and with respect to strategies and expectations, that teachers should not assume good inquiry will lead to correct knowledge.

This familiar epistemological point should be connected to what is becoming a familiar pedagogical point—that teaching is inherently uncertain. That teachers and instructional materials cannot determine what students will discover, for epistemological reasons, contributes to other uncertainties, of socioeconomic, physical, psychological, and cultural origin. Still, as McDonald (1992) warned, assumptions and esthetics of certainty are embedded in practices at all levels of the educational system, from the detailed lesson plans that intern teachers prepare in traditional programs, to education research that evaluates curricula through experimental and control groups, and to publishers’ book fliers touting “classroom techniques that really work.”

These assumptions of certainty play a significant role in the tension between student inquiry and traditional content. The latter almost inevitably reemerges as the bottom line, largely because it affords a semblance of certainty in planning and assessment. It seems straightforward for a teacher, and for students, parents, and school administrators, to assess progress with respect to traditional content: How many chapters has the class covered? How many exam questions did a student answer correctly? In contrast, despite educators’ views of the importance of

³This point is often misinterpreted to support an untenable, unproductive relativism. That physicists’ notions of electricity and conduction are constructed does not imply that they are arbitrary. To the contrary, the histories of their construction recommend these notions as distinctive and unusual with respect to their usefulness for explaining and predicting phenomena in the physical world. Other constructs, such as Greg’s “same material” account, do not share this distinction: Wires made from Styrofoam™ would not function. Current postmodern esthetics notwithstanding, there is a substantive epistemological basis in physics for designating certain ideas as incorrect.

inquiry-oriented objectives, in themselves and as likely prerequisites for traditional content-oriented progress, our understanding of those objectives and how to assess their achievement remains vague and uncertain. The problem with “less is more” is that, whereas it is quite tangible in what sense a course is “less” (fewer chapters, fewer concepts), it is rather more difficult to discern in what sense it is “more.”

The main approach to addressing this problem has been to pursue an understanding of scientific inquiry that is comparable in quality and reliability to the knowledge available about physical phenomena. Few would suggest this has been achieved, although educators have often invoked research into the nature of scientific reasoning and its development to define specific inquiry-oriented objectives, such as in the frameworks noted earlier of reasoning abilities and process skills (Gagné, 1965; NRC, 1996).

The tension between inquiry and traditional content has generally been perceived and addressed against an unexamined, background assumption of certainty. It is perhaps for this reason that the role of the teacher in discovery learning is seldom examined (A. Brown, 1992). My purpose in this article is to examine that role, focusing in particular on this tension. To that end, following McDonald (1992) and others, I will recast the matter against a background assumption of uncertainty. This recasting will not rule out contributions of research or of frameworks specifying inquiry-oriented objectives, but it will shift the nature of those contributions.

DISCOVERY TEACHING

Views of teaching as uncertain and contingent have been developed in various accounts of teachers as reflective practitioners (Schön, 1983) engaged in practical inquiry (Cochran-Smith & Lytle, 1993; Richardson, 1994) and improvisation (Sassi & Goldsmith, 1996). They are manifest in a growing literature of detailed, narrative accounts of classroom practices, including those in science and mathematics (Ball, 1993; Lampert, 1989, 1990; Minstrell, 1989; Roth, 1995; Schifter, 1996; Warren & Rosebery, 1996).

One might describe the instructional practices in these accounts as *discovery teaching*. All teaching, like all learning, involves discovery. What distinguishes these practices is a stance of inquiry wherein teacher discovery plays a central, essential role in shaping the substance and form of the course. Curriculum, in this sense, is not determined entirely in advance; it is largely discovered and emergent.

Ball (1993), for example, recounted an episode from her third-grade class that started when “Sean announced that he had been thinking that six could be both odd and even because it was made of ‘three twos’” (p. 385). As the teacher, Ball deliberated whether to “introduce to the class the idea that Sean has identified (discovered) a new category of numbers” and worried about confusing them with “nonstandard knowledge” but saw an opportunity to “enhance what kids are thinking about ‘definition’ and its role, nature, and purpose” (p. 387). She chose to

proceed, drawing contributions and arguments from other students and eventually coaxing a definition of *Sean numbers*: “‘Sean numbers have an odd number of groups of two.’ And, over the course of the next few days, some children explored patterns with Sean numbers, just as others were investigating patterns with even and odd numbers” (p. 387).

In this way, Sean numbers contributed to the substance of the course. This was discovery learning, but it was also discovery teaching, dependent on Ball’s (1993) discovery of the mathematics in Sean’s announcement and of the opportunity it presented to promote the students’ understanding of mathematical inquiry. It was also an example of a teacher negotiating the tension between inquiry and traditional content; to Ball it was a “dilemma” between “respecting children as mathematical thinkers” and helping them “to acquire particular tools, concepts, and understandings” (p. 384).

Lampert’s (1989) accounts similarly depict her “examining” (p. 235), forming “conjectures about” (p. 238), and “choosing mathematical representations that are responsive to” (p. 241) her elementary students’ mathematical thinking (see also Lampert, 1990). Minstrell (1989) described his perceptions of students’ contributions and his in-class decisions during a discussion about the concept of force, speaking of the curriculum as evolving and contingent on the teacher’s sense of the students’ “conceptual and rational needs” (p. 131). Roth’s (1995; Roth & Roychoudhury, 1993) articles have focused on analyzing students’ participation, but his accounts also exhibit his stance of inquiry as the teacher in the classroom.

Ball (1993), Lampert (1989, 1990), Minstrell (1989), and Roth (1995; Roth & Roychoudhury, 1993) were writing about their own teaching, as I am here, but discovery teaching is by no means the invention or property of researcher teachers. Few full-time teachers who assume such a stance of inquiry in their work have the time and occasion to make public presentations. Some do: Schifter (1996) edited a collection of essays by mathematics teachers concerning their inquiry into their students’ and their own mathematical thinking. LabNet (Ruopp et al., 1993), an electronic network of teachers interested in “project enhanced science learning” includes accounts by those for whom projects are a primary means to develop the substance of a course. Teacher perception, judgment, and discovery are central in these approaches, as has been depicted by such teachers as Donna Holmes, Robert Kitchen, Greg Lockett (see also Lockett, 1996), and Kelly Wedding. Other accounts of teacher inquiry are presented in articles by researchers with whom the teachers collaborate, such as Rosebery’s and Warren’s (Rosebery, Warren, & Conant, 1992; Warren & Rosebery, 1996) accounts of middle school science classes.

AN OVERVIEW OF THIS ARTICLE

Popular appreciation and academic discussion of issues facing teachers often center on general matters such as the challenges of coping with difficult conditions in

urban settings, cultural and sexual inequities, and discipline and motivation. Perhaps because these challenges are so great, matters pertaining to intellectual substance, or content, which are often studied carefully in research on students' knowledge and learning, are largely ignored or taken for granted in research on teaching. Important exceptions include work cited earlier in elementary mathematics (Ball, 1993; Lampert, 1989, 1990; Schifter, 1996), in history (Wilson & Wineburg, 1993; Wineburg & Wilson, 1988), and in more general discussions of pedagogical content knowledge (L. S. Shulman, 1987; Wilson, Shulman, & Richert, 1987). There is (or should be) a great deal of physics in a physics course, and that substance is the central concern of this article.⁴

To summarize this introduction, much of the challenge for teachers lies in coordinating inquiry and traditional content-oriented objectives. How teachers understand and undertake that coordination depends largely on their more general assumptions and esthetics. For those who expect certainty and control, at least with respect to the substance of instruction, the challenge takes a different form than it does for those who expect uncertainty and adopt a stance of inquiry. The purpose of this article is to explore this coordination, taking the latter view of teaching, from which it is centrally a matter of teacher perception and judgment and from which discovery learning depends on discovery teaching.

The following section recounts a week from a high school physics course, as complete and detailed as is practicable. I intend this account as an authentic example (as opposed to a model) of discovery learning and discovery teaching—to provide a context in which to discuss the role of teacher perception, inquiry, and judgment in shaping the substance of learning and instruction. The final section, *Teaching From a Stance of Inquiry*, suggests implications for teaching and teacher education.

A WEEK FROM A HIGH SCHOOL PHYSICS COURSE

This course took place over the 1992–1993 school year at a local public high school where I taught as a guest. The class met daily, for 42 min, except on Mondays when we had a double period. There were 22 students (11 boys and 11 girls); 16 were seniors, and 6 were juniors. I videotaped every meeting from the 3rd week of school through April 1 (except for occasional technical problems) and recorded a detailed journal immediately after each session. The following account is based on the

⁴The amount of physics in this article will probably present a problem for some readers. The appendixes provide explanations of the main ideas and terminology, but it would be strange for me to presume that these will be sufficient—that readers can learn physics by reading explanations. But I am not aware of a more adequate solution. This may be one reason that matters of substance are not more generally addressed in research on teaching: It is difficult to do so in a manner accessible to an interdisciplinary audience.

TABLE 1
Calendar of Class Meetings

February 23–26 (Tuesday–Friday)	Getting started with Electrostatics Activities
March 1–5 (Monday–Friday)	In-class science-fair project presentations
March 8–12 (Monday–Friday)	Resumed work with Electrostatics Activities
March 15–17 (Monday–Wednesday)	No class
March 18–19 (Thursday and Friday)	Discussion and quiz
March 22–31	Continued work with Electrostatics Activities

videotapes with transcripts, the daily journal, and my reconstructions later on viewing videotapes and reading transcripts and journal entries.

I describe roughly 2 weeks of classroom activity, as summarized in Table 1, with particular attention to the week of March 8–12. Unlike most of our work over the year, this unit was based on a set of predesigned and commercially available curriculum materials—Electrostatics Activities for Students⁵ by Robert Morse (1991)—and thus affords reflection on the role of such materials in shaping classroom interactions.

There are two sections to this account, describing our work in chronological order. The first section emphasizes teacher interactions with students working in groups, to consider the role of teacher perceptions and judgments with respect to particular students and groups in the coordination of inquiry and traditional content-oriented objectives. The second section emphasizes whole class discussions in order to consider the coordination of these objectives at the level of the evolving substance of the unit, or, as I will call it, the *emergent curriculum*.

Group Work: Student and Teacher Inquiry and Discovery

The coordination of student inquiry and traditional content objectives need not be understood as simply a matter of making decisions about content, coverage, and method or as a uniform decision for the class as a whole. It can vary dramatically, depending on what the teacher perceives in particular moments with particular students. This section concerns teacher perception, inquiry, and judgment regarding students' work in groups with discovery learning materials.

I begin by describing the classroom activity over the 4 days in February when we started with the materials and, in greater detail, the group work during the

⁵I came to use these materials when I became involved, as a consultant for LabNet, in a focus group led by Patty Rourke and Greg Lockett. This was an experiment in collaborative inquiry among a group of physics teachers conversing by electronic mail about our experiences teaching from a common set of materials. Rourke and Lockett chose Morse's (1991) materials, which they felt could support teachers' transition to project-based instruction.

meetings on Monday, March 8, and Tuesday, March 9, when we resumed work with materials after a week-long hiatus for science-fair presentations. I then reflect on my perceptions and intentions and on their role, from group to group, in the coordination of student inquiry and traditional content.

February 23–26: Developing a sense of the task. Electrostatics Activities for Students (Morse, 1991) is a set of worksheets (see Appendix A), including plans for simple devices made from inexpensive, everyday materials (e.g., adhesive tape, disposable plates and cups, plastic straws, aluminum foil) and instructions for using them to explore phenomena in electrostatics. We began work on Electrostatics Activities on Tuesday, February 23, the first day back after winter vacation. The first sets of activities had the class using adhesive tape to explore electrostatic attraction and repulsion (see Appendix B). As usual, the students chose their own lab partners and tables. They worked in pairs, with two pairs at each table, but there was often enough interaction between pairs at a table to consider them a single group of four.

I was disappointed by the students' initial approach to the materials: They were trying "to get the result that they thought they were 'supposed' to get" (daily journal, February 23) and to make their way through the worksheets rather than to build an understanding. Prior to this unit, I had felt that we had established practices of authentic inquiry and sense making, but now the students seemed to have regressed, and I was irritated by what I saw as cynicism and apathy.

At one point, however, two students (Steve and Bruce) complained about the worksheets, telling me in essence that they were unhappy being asked to make things without knowing why ("We don't even know what it's for!"). Several others had protested that the worksheets were "redundant," but it was Steve and Bruce's complaint that prompted me to understand that, from the students' perspective, they were doing what I was asking them to do, and some of them were not any happier about it than I was.

For these students, accustomed to using worksheets in science courses, the materials evidently signaled a familiar form of activity. I decided I needed to address their understanding of the task, rather than, for example, their motivation. To that end, I set out to recast the worksheets as tools for the students to use to support their learning. I told them to proceed in the worksheets only if they did not have any questions or ideas of their own for things to try, and I encouraged them to skip questions they felt were redundant or for some other reason not useful to their learning. This seemed to have the intended effect, perhaps a sign of progress after all from the start of the year when it had been much more of a struggle to engage the students in directing their own inquiry (Hammer, 1995a).

We had only Tuesday through Friday of that week to work on the new materials; the following week was reserved (by school policy) for in-class presentations of science-fair projects. We returned to Electrostatics Activities on Monday, March 8.

March 8: "The stand might be charged, too." We had spent the first half of Monday's double period finishing with and discussing science-fair projects. I was not happy with the students' work, for the same reason that I had not been pleased with their initial approach to the worksheets: Most followed what they understood to be the required form of a science-fair project rather than engaging in meaningful inquiry. As with the worksheets, it came out in our conversation that the students felt they were doing what they had been told, and they did not find it meaningful either. We were all disappointed in ourselves: I faulted myself for not keeping adequate track of their work, and we ended the discussion in a somber mood.

In the second half of the double period, we returned to Electrostatics Activities. The mood persisted, but students made progress. Almost everyone worked on Section 4 (Appendix A), which involved building and experimenting with an electrophorus—a device for storing electric charge. Here it consisted of an aluminum pie plate with a Styrofoam™ cup taped to it as a handle or a stand. Most students needed guidance through the step in Section 4.1C of touching the aluminum plate with a finger while holding it near a charged foam plate.⁶

Jean, Greg, and Jack had all done well with their projects and were one of the few spirited groups (Jean's partner, Julie, was absent). Working in Section 4.2A, they had attached a foil-covered straw to the electrophorus plate and charged the electrophorus. Following the directions, they brought the foil straw near their "pith ball," in this case a tiny ball of aluminum foil, and saw that the pith ball was first attracted to the straw and then repelled strongly away.⁷ Jean called out "I don't get this!" to summon me to their table, and they showed me what they had seen. Greg speculated that "the stand might be charged, too," referring to the metal stand from which the pith ball was suspended by a string. Jean asked me, "Wouldn't it be something like, you know how they say closed circuits and stuff like that with electricity?"

I was curious about Greg's idea that the stand might be charged, but I was more concerned by Jean's question, which I saw as a move to deflect the problem away from her own thinking. She was one of a few students who still, at this point in the year, often distrusted the value of students' discussing their own ideas. I responded to Jean, "I don't know what 'they say.' What do you know from what you've been doing here?" At that moment, Ning, sitting at a desk behind Greg, chimed in with her explanation for the pith ball's repulsion from the electrophorus: that when it touched the electrophorus, it took on the same electric charge. Greg dismissed it, however, saying, "It just doesn't sound right." He had another idea, that the pith ball might be negative on one side and positive on the other, and drew a picture similar to that in Figure 2.

⁶See Appendix B for an explanation of why this step is necessary for charging the electrophorus.

⁷See Appendix B for further explanation of the pith ball.

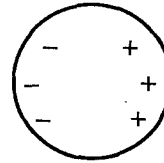


FIGURE 2 Greg's idea about the charge on the pith ball.

- Greg: Just say this straw is positive, right, [and] say all this side [of the pith ball] was negative, and like these came together.
- Jean: All right, so this [indicating the foil covered straw attached to the plate] is positive and that's [indicating the pith ball] all negative.
- Greg: Well, not—
- Jean: On one side.
- Greg: Right. Say that side was all positive.
- Jean: So it's neutral [the pith ball].
- Greg: Right. So I figured this [the pith ball] might have turned around, so that these were all positive and these turned to be negative.
- Jean: Oh, I didn't—
- Greg: Like, not turned, but, like, because of the way it went, and then that made it repel.
- Teacher: What do you think about that Jean?
- Greg: I'm not sure. It's an idea.
- Jean: So, what he's saying is, what he's saying is so it's kind of like a magnet. On one side it has these poles, and the other—
- Greg: Right.
- Jack: Yeah.
- Teacher: And somehow it slides around to its positive side.
- Greg: Yeah, right.
- Jean: Yeah, that's what he's saying, right.
- Teacher: What would make it flip around?
- Greg: I don't know.
- Jean: I know that's what I don't understand.

Much of this the students were intended to have discussed in Section 4.1C, which was designed to focus attention on the pith ball's repulsion and to guide toward the idea that it must have acquired the same charge as the electrophorus. (Section 4.2A was designed to help students distinguish between a conductor [the foil-covered straw] and an insulator [the plastic straw].) In fact, I thought Greg, Jean, and Jack had arrived at that explanation, so I was surprised they did not quickly recognize Ning's interjection as correct. Perhaps they felt she was intruding, or perhaps they were focusing on the pith ball's initial attraction, which that explanation did not address.

I was pleased, however, both by Greg's idea and by Jean's attention and effort to understand it. It was partially correct: The initially neutral pith ball does become polarized in this way, with positive charges on one side and negative charges on the other, and this accounts for its attraction to the charged straw. But Greg was describing this charge distribution as fixed rather than induced: A positive charge on the straw would cause, or induce, the distribution on the pith ball by attracting negative charge to the near side of the pith ball and repelling positive charge to the far side.⁸ Moreover, Greg was not thinking that the pith ball could acquire a net positive charge from hitting the foil-covered straw. I saw his idea as the beginning of a physicist's understanding, but I was not concerned that he and his group develop it fully here because there would be more opportunities. So I questioned his idea on its own grounds, asking what would make the pith ball turn around, without trying to guide toward my explanation.

The question prompted Greg to return to his earlier idea that the stand might be charged. He pointed to a bit of corrosion, which he knew, from his nautical experience, was related to electricity. Jean suggested they repeat the experiment holding the pith ball's string by a hand instead of tying it to the stand. Greg worried that "You might be charged, too," but he thought that rubber would work, because "It blocks electrical current." I left them there, feeling that other groups needed my attention and pleased that they were coming up with ideas and finding ways to explore them. (Jack did not seem involved, but I chose not to press him. He was generally doing well in the course, and at the time, he was preoccupied with his science-fair project, which he was revising and improving to present at the school's fair later in the week.) At the end of class, they told me they had tied the pith ball to the rubber casing of a power cord from the room's overhead projector. They had obtained the same results, so they ruled out charge in the stand as an explanation for the phenomenon.

Their conclusion was progress toward the understanding I wanted them to develop, because it ruled out a misleading explanation. The reasoning and experimentation that led them to this explanation, on the other hand, were in various ways misleading in themselves: Rubber and foam are both insulators. They can both have charge; what neither can do is conduct charge.⁹ Nevertheless, based on what they knew and had experienced, I thought they were being creative, resourceful, and scientific in designing an experiment. I remained concerned about maintaining their stance of inquiry, after the class's initial fill-in-the-blanks approach to the activities, and about Jean in particular, who seemed ever ready to defer to what "they" (or I) might say. Moreover, as with the idea of induced polarization, there would be many further opportunities for them to distinguish conductors from insulators and charge from current. I chose simply to compliment them: "Good experiment. That was great."

⁸See Appendix B for further explanation of induced polarization.

⁹Corrosion is caused by electrical current and not by the presence of charge.

Elsewhere in the class, Sean had not begun to work on the activities, and I lent him my set of worksheets rather than allow him to retrieve his from his car. Other students I mentioned in my journal that day were Ning, Wei, Liu, and Joanne who, working on Section 4.1C, had found the explanation Ning suggested to Greg's group: that the pith ball repelled because it picked up the same charge as the electrophorus plate. But they had also seen, at least once, the pith ball repel and then suddenly attract again, clinging a second time to the electrophorus. Their explanation did not account for that behavior, and they asked me for help. I was very pleased by their work, both because they had arrived at and seemed confident in the "correct" explanation and because they were working to make sense of some anomalous behavior they had observed. They tried to reproduce it, and I tried with them to come up with ideas for what might have happened. To guide them toward what I felt was probably the reason for what they had seen, I asked if the pith ball might have hit something on its quick repulsion from the electrophorus. Wei told me he thought it did hit a metal stand nearby. When I asked them what hitting the stand might do, Joanne and Wei both suggested it might change the charge on the pith ball, and we decided that this solved the puzzle.

March 9: The "same material" explanation. The class was much more lively on Tuesday, with a nice feeling of engagement and productivity. Greg called me over as soon as the period began to say he had found an explanation for the pith ball's behavior in our long-forgotten textbook's¹⁰ account of induced polarization. I was impressed and pleasantly surprised, mainly by his initiative: Greg was one of the better students in the class with respect to his intuitions for physics, but he was not one of the better students at getting work done outside class.

At the same time, I was put off balance by this unexpected voice of authority. I asked Jean, Jack, and Julie if the explanation made sense, and they nodded too quickly that it did. I was not so much concerned that they genuinely understood it at this point. What worried me was that the "right answer" from the textbook had stopped them from thinking for themselves. At the moment, however, I could not think of any graceful way to address that worry, and other students were looking for my attention, so I simply congratulated Greg for his initiative.

Later in the period, working in Section 4.2, that group arrived at their "same material" explanation recounted at the opening of this article. They had invented, designed experiments to test, and confirmed an explanation by which charge conducts from foam to foam. I was torn, both over how to assess what they had done and over how to proceed. With respect to traditional content, assessment was straightforward—their account was false—but I was unsure how to assess it as inquiry. The explanation was their own invention, and it was consistent with some

¹⁰I had not assigned anything from the textbook since November because I felt it was not helpful for these students (Hammer, 1995a).

of what they had observed in the lab, but it was not consistent with what I thought they must have known from common experience: that metal conducts electricity.

I had other concerns as well: Greg and Jean were doing all the work. Jack was still mostly uninvolved, and Julie, whose work in the course went through cycles of excellence and withdrawal, was in a withdrawal cycle. I tried to draw them in, directing questions their way, with modest success, but I felt there was little else I could do. I trusted Jack would reengage after the school science fair, and I had been trying for most of the year to understand and influence the swings in Julie's participation.

Watching their experiment, I saw that they were holding the charged plate in such a way that it was close enough to the pith ball to affect it directly, whether or not the cup acquired a charge. I chose to intervene, as I described after class in my journal:

I said, "Well what if I put the cup over here, so that it's just touching on the edge and I can be sure that plate's charge doesn't have an effect." I was a little uncomfortable in my interaction with them because it really felt [as though it was implicit that] I knew the right answer, and I was trying to manipulate them to do that experiment that gets them the right answer. ... I'm not sure I did that well. (daily journal, March 9)

In this way, I helped them reconstruct the experiment to give the appropriate result, but I was uncomfortable, largely because of my sense of the different needs of the different students. For Jean in particular, I worried my intervention would corroborate what she suspected all along—that, in the end, this was about "getting the right answer," and all of this exploration was a kind of sham.

I was not so torn at other tables. Nancy, Susan, Bruce, and Steve, also working on Section 4.2, had found a plastic straw that appeared to conduct electricity.

Teacher: Do it again. [watching] That's pretty weird. It still does it.

Nancy: It's inside the straw, that's what I think. It's coming through the straw.

Teacher: It's coming through the straw [laughs]. Well, you got what you got. That's pretty cool.

Bruce: [obviously pleased] We weren't supposed to get that, right?

I answered Bruce by saying that this was not what I had seen when I tried it. Nancy speculated that it might have something to do with whether the straw has its ends taped closed; Susan suggested that, if the ends are closed, "the charge can't leave," perhaps picturing charge filling the interior of the closed straw. Steve thought that the straw itself was somehow "different." Like Ning's group the day before, they knew what they were "supposed to get," but they were trying nevertheless to make sense of what they got.

At first, I thought Nancy was joking about charge “coming through the straw,” partly from her tone of voice but probably also because, to me, the shape of the straw was obviously irrelevant. When I returned to check on their progress later, they were still discussing the idea, having explored it further.

Nancy: The straw was closed up, and nobody else’s was; it’s all open. We left the straw open, and now it doesn’t work.

Steve: It’s also a different straw.

Nancy: It’s also a different straw.

Teacher: So why does [leaving the straw open] make a difference?

Nancy: I don’t know.

Susan: Because things can’t get out. The charge can’t leave.

They tried a series of other straws and consulted with other groups, but they could not find or produce another conducting plastic straw. I suggested the strange straw might have some kind of residue in it, but, I said, I did not know why it was conducting.

I had little to say about this interaction in my journal. All I noted was that they had found a conducting plastic straw that I had seen with my own eyes and could not explain. From my interactions with the students on the videotape and from the lack of mention in my journal, I did not seem to be concerned about Nancy and Susan’s “closed ends” line of reasoning. Perhaps I expected them to drop it on their own.

At the next table, Ning, Liu, and Wei were confident that the pith ball repelled from the electrophorus because it picked up the same charge. Perhaps to confirm their explanation or perhaps just “playing,” they tried to detect the pith ball’s charge with a foil-leaf electroscope (another device to detect charge, which I had made available). To their surprise, the electroscope did not indicate a charge on the pith ball, and they were trying to understand why. When I checked with them later, they had several ideas, all consistent with their previous account of the pith ball’s repulsion, including Wei’s thought that “the charge is not significant enough” to affect the electroscope, which was the essence of my own explanation. (Much more could be said about why the charge is so small.) I told them I thought they had several reasonable possibilities, was happy to see them trying to reconcile the discrepancy, and was not concerned that they arrive at what I considered the correct explanation.

Scott and Sean were starting Section 1, well behind everyone else. They were both very capable, with class contributions that were often remarkable, but neither kept up with the work, largely because they both held nearly full-time jobs outside school. I listened in on Ricky and Tim, who were working on Section 4.1. They were both juniors, rarely contributed to class discussions, and often had trouble staying on task in groups, but they seemed to be doing well with these activities. I

did not spend much time with Penny and Camille either, who also seemed to be working well.

Mona and Amelia were working at the same table as Harry and Andy. Mona explained, when I asked, that the pith ball is repelled because it picks up the charge of the electrophorus. She was almost always passive and uninvolved, and I was very pleased to see her engaged and apparently gaining insight into the physics. Had it been Amelia, one of the most active participants, I probably would have remained neutral, but I told Mona "Wow, that's great!" and gave her a "high five."

Later, Amelia called me over to ask about the question in Section 4.2C: "How did the foil-covered straw get charged? How did the pith ball get charged? How is this different from the way that the tapes and foam got charged?" (*Tapes* here referred to the activities of Section 2, in which the students charged pieces of transparent tape by peeling them from surfaces and from each other.) Amelia had the idea that "There wasn't any charge yet," but for the foil-covered straw and the pith ball "You just transferred charge that already existed; [for the foam] you have to form a charge." It was a very good answer, making substantial progress toward the traditional content I (and the worksheet) intended. Andy and Harry were skeptical, and Amelia tried to convince them. I tried to help her explain her idea, reiterating her explanation, but I pointed to what I thought was still missing: figuring out "how do you form the charge." That, I told them, would be homework for the next day.

After class, Amelia approached me with an idea for an answer to that question, recounted later when the narrative resumes. Here, I pause to reflect on my perception and judgment during these classes, from student to student and group to group.

Teacher Perception and Judgment

The tension between inquiry and traditional content is generally reckoned as a matter of curriculum, defined in terms of materials and methods and addressed through decisions such as that to use the Electrostatics Activities. These decisions are important, and they do much to frame the substance of a course, but they do not determine the flow of learning and instruction. It remains for the teacher to discover how students engage the materials and what they might accomplish.

Thus, the students in these classes did not always interpret the instructions and questions as intended, and even when they did, they did not always arrive at the intended answers. The worksheets were not designed to coax students into complacency, but, for these students, they seemed at the outset to have that effect. My response was to tell the students to use their judgment about when and how to proceed through the worksheets. That stirred new uncertainties, as the students digressed from the prescribed activities to pursue their own questions and experiments, including, over these 2 days, suspending a pith ball from a rubber-cased

power cord, touching a pith ball to an electroscope, and investigating the anomaly of a conducting plastic straw.

All teaching involves such perceptions and discoveries, some simple and mundane (they need help with the step in Section 4.1C) and some more substantial (they have not distinguished the concepts of charge and current); some concerning the class as a whole (they have regressed to filling in the blanks), some concerning particular groups (Greg, Jean, and Jack think the stand might be charged), and some concerning individual students (it was Mona who gave the explanation).

From a view of teaching as discovery, the class is an arena for teacher exploration of students' participation, knowledge, and reasoning, and what the teacher finds in that exploration informs her or his sense of the objectives and how they might be achieved. Coordinating traditional content and student inquiry is not simply a matter of reducing the former and accepting the latter; it is a matter of discerning students' strengths and needs, and these may vary considerably, in specific instructional moments, from student to student and group to group. In this way, successful instruction depends on successful perception and judgment.

Working with Greg, Jean, Julie, and Jack, for example, I was torn over how to proceed, reluctant to share with them my opinion of their "same material" idea and experiments. But I had no qualms about telling Nancy, Steve, Bruce, and Susan what I thought about their conducting plastic straw. The difference was in my perceptions of their work. Greg's group, as a group, seemed inclined to accept a voice of authority without further question rather than to use it as a basis from which to reevaluate and reconstruct their understanding. Nancy's group, in contrast, seemed inclined toward a sense-making approach, and I was not worried that my input would interfere. At the same time, Greg's group seemed more at risk of arriving at an understanding inconsistent with my traditional content-oriented agenda. They had concluded that their "same material" explanation was correct, that a Styrofoam™ object will conduct to other Styrofoam™ objects, whereas Nancy's group was skeptical of their conducting straw.

Perceiving different strengths and needs, my agenda shifted. Nancy's group seemed established in a stance of sense making, and I felt in a position to challenge them further, with respect to traditional content as well as inquiry, toward coherent argumentation and reasoning. Greg's group did not, and I took it as a central agenda, working with them, to promote such a stance.

Instruction goes awry, on this view, not because it fails to proceed as planned but because the instructor either misperceives the students' participation or is unable to respond to what she or he does perceive. Moreover, all instruction goes awry in at least some respect. First, there is simply too much at any moment to perceive, let alone to address. It would not have been possible, for example, for me to focus simultaneously on Julie's apathy, Jack's distraction, Jean's epistemology, and Greg's conceptual understanding, to consider only a single group. Second, some of what there is to see, in practice if not in principle, is beyond the teacher's

influence. I felt I understood why Scott and Sean did so little work for the course—their 30-hr after-school jobs—but I also felt there was little I could do to change the situation.

Third, what shapes a teacher's intentions and interventions is not what is happening but what the teacher perceives is happening, and what the teacher perceives depends as much on the teacher's knowledge, beliefs, and attitudes as it does on the classroom events. Thus, this account describes my perceptions as the teacher. I cannot suggest they are reliably accurate; certainly they were not complete. Others watching the same students perceive their work differently.

At the time, for example, I assumed students would think of conductivity as a property of the material (metal or plastic), and it did not occur to me they might focus on the shape. So I thought Nancy was joking when she talked about whether the ends of the straw were open or closed. In retrospect, considering what she had seen and experienced, her idea was perfectly reasonable. Similarly, I was taken aback by Greg's "same material" reasoning. At the time, as I noted earlier, it troubled me that the students were willing to abandon their everyday knowledge that metals conduct. Reflecting on the interaction as I prepare this article, I question that perception: Perhaps it was not that they were abandoning their everyday knowledge but that they were not thinking of this as conduction. Examining the transcript, I now discover, they described charge as *spreading* and *shared* and *distributed* around the Styrofoam™, but never as *conducted*. Now that I have discovered these possibilities, I may be better equipped to recognize them should they come up in my teaching again.

Class Discussions: The "HAM" Theory and the Marino Phenomenon

The previous section concerned teacher perceptions and intentions with respect to particular students working in the course; this section concerns the evolution of the course. Often what a teacher observes while working with particular students is, in the teacher's judgment, worth the attention of the class as a whole, and the teacher may choose to elevate that question or idea to the level of curriculum. In this sense, the curriculum, that is the substance of the course, emerges from student and teacher inquiry and discovery.

In this section, I return to the narrative of the classroom activities, this time to consider the coordination of traditional content and student inquiry at the level of the emergent curriculum. I begin again with an account of the classroom activity—here divided day by day for March 10, 11, 12, 18, and 19—focusing on what became two key pieces of our curriculum: the HAM theory and the Marino phenomenon. I then reflect on the role of teacher perception and judgment in that evolution.

March 10: Amelia's explanation. Amelia approached me after class on Tuesday to tell me that she had an answer to the question of how a charge is formed in peeling apart two pieces of tape (see Appendix B). Her idea was that peeling the tapes apart did not "form" charge but "separated" it. She explained that the tapes had both positive and negative charges at the outset but that they "canceled each other out." Peeling the tapes apart, she said, separated positive and negative charges, leaving two oppositely charged pieces of tape, as shown in Figure 3. This was both what the worksheet question was designed to elicit and much of the explanation I wanted students eventually to understand. I told her we would be discussing this topic the next day as a class, and she should be sure to present her idea.

Amelia presented her idea early in our discussion the next day. Camille, whose participation in the course was sporadic, was nodding as Amelia spoke, and I took the opportunity to draw her in as an early supporter of an account we would eventually validate as "what physicists think."

Teacher: Camille, [you seem to think] that's an important point.

Camille: When the tapes [are] together, they cancel; all of the charges cancel; you can't tell if it has any charge. When you rip them apart it only makes an act of—

Amelia: You separate the charges.

Camille: It brings the charge out, like.

Harry asked Amelia why she thought the tape could not hold both kinds of charge, and Scott asked why the charges would cancel if the tapes had the same charge, evidently not understanding Amelia's idea. Amelia reiterated her explanation, with help from Susan. Penny asked why the tapes would have different charges "if they are the same material," but Amelia did not seem to understand her question.

Ning, who was also taking chemistry, connected Amelia's idea to the atomic model of a positive nucleus with an equal number of negatively charged electrons.

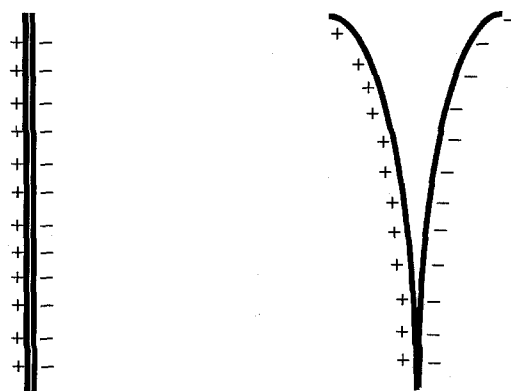


FIGURE 3 Schematic depiction of Amelia's explanation. On the left, the two pieces of tape are stuck together, with no net charge. Peeling the pair apart separates positive and negative charges.

Removing or adding an electron, she said, “makes the atom become positively charged or negatively charged.” Harry still felt that, by this explanation, “You create the charge,” and that when an object is neutral “There’s no charge.” I was not sure whether he was being uncharacteristically obtuse, arguing a point of semantics, or simply being contrary, but Susan, Nancy, and Ning responded that “There’s no total charge,” that the charges are there but “together,” and Harry surrendered the point.

I drew a diagram of Amelia’s idea on the board, similar to that in Figure 3, identified it as “a model for how the tapes get charged,” and asked the students to critique it and consider its implications for other phenomena they had seen:

Teacher: Is that a good model; is there a problem with it? ... If this is what happens with a pair of tapes, then what happens when I take the rabbit fur and I rub the foam plate?

Joanne built on Ning’s idea with something she remembered from chemistry:

Joanne: Some objects, like, tend to give up electrons more easily than other objects, and another object is going to take them more easily. You know what I mean?

Teacher: How do you know that?

Joanne: Chemistry. You know what I mean? ...

Amelia: That’s why it depends on what kind of material you use to what kind of charge you get.

This was further progress toward the understanding that the worksheets were designed to promote: The structure of some substances leaves room for an extra electron or two, whereas the structure of other substances tends to crowd out electrons. Rubbing a piece of rabbit fur against a Styrofoam™ plate lets overcrowded electrons in the fur move into the available spaces in the polystyrene of the plate, leaving the fur with more protons than electrons and the plate with more electrons than protons. I was delighted not only by this progress but also by the way the ideas were emerging and from whom. Joanne and Camille, in particular, were seldom principal protagonists in the development of substance, and although Amelia often spoke in class, her views had seldom survived scrutiny.

With the students taking care of the traditional content, I focused on drawing them into reasoning practices of assessing their account for its implications in other situations. As part of that, I tried to avoid closure with respect to the theory I considered correct. For the remainder of the period, I enjoined them to consider what the model would predict (“So if that’s right, what would happen if you rub two foam plates together? Should you be able to get a charge on them?”), whether it agreed with everything we already knew and whether there were any reasonable alternative explanations. Of course, my intentions were not purely inquiry oriented

because I hoped and expected this would prompt the students to explore the ideas more thoroughly and develop a more robust understanding.

We decided it should not be possible to charge two foam plates by rubbing them together, because, as Amelia said, “They have the same tendency of attracting or repelling” electrons. We also decided the model would predict that the charge on rabbit fur should be opposite the charge on the foam plate, after they are rubbed together, and we discussed how these predictions could serve as empirical tests of the model.

To resolve one apparent discrepancy and to avoid a confusion that might have undermined this progress, I volunteered an answer to the question that Penny had asked but we had never addressed: Why would peeling two pieces of tape apart give them different charges, if they are the same material? Perhaps, I suggested, there are two materials involved, glue and plastic, because the two pieces of tape were stuck together with the sticky side of one in contact with the non-sticky side of the other.

Ning reported, as counterevidence to the model, that she had charged two pieces of rabbit fur by rubbing them together. Amelia and Joanne responded that the pieces of fur also had two sides, so Ning might have been rubbing different materials. I commented that Amelia and Joanne were behaving “like true scientists,” trying to explain away Ning’s counterevidence to keep their model standing, and I suggested that someone should try to replicate Ning’s results. The only alternative explanation anyone could think of this day was that the charge from rubbing might be caused by heat generated by the friction, in which case it should be possible to charge two foam plates by rubbing them together. The students rejected that explanation quickly because it would mean a hot frying pan should show a strong electric charge.

March 11: Camille’s discovery. Several students were absent Thursday, including Ning, Steve, Jean, and Jack, who were dismissed to set up their presentations for Friday’s school science fair. The rest of the class worked in groups: Nancy, Susan, Greg, Bruce, and Mona worked together testing the predictions of the model from the previous day. The “same material” explanation came up again in two other groups. (Greg, however, denied ever having the idea.) Camille mentioned it briefly but dismissed it immediately on hearing Joanne talk about conductors and insulators. (“She’s right, I know she’s right.”) Ricky and Tim disconfirmed it with an experiment using two plastic straws, one charged and the other neutral, and Ricky revised his explanation to say, “One’s a metal; it’s a conductor, and the other one isn’t,” which Tim said he already knew.

Two groups, Andy, Liu, and Wei and Joanne, Camille, and Penny, were confused about the question in Section 4.4 asking for cartoon-like diagrams of how they understood the motion of charge in the electrophorus. They were, instead, simply sketching their observations. I tried to explain what the question was asking, but

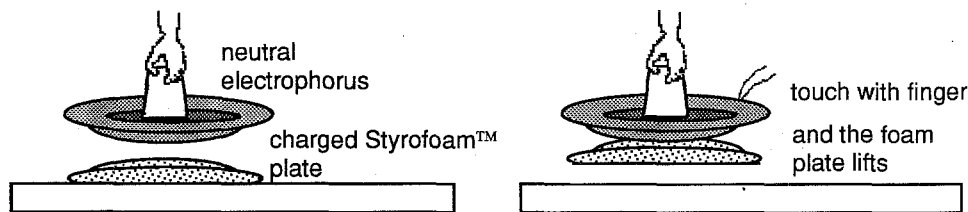


FIGURE 4 The Marino phenomenon. Hold a neutral electrophorus by its foam cup handle, and bring it close to a charged foam plate. Touch the electrophorus plate, and the foam plate lifts from the table.

either they did not understand the nature of the task, or they did not see it as useful. I became concerned that our conversation was shifting from the substance of their understanding of the physical mechanism to the required form of response. I thought drawing the diagrams would be helpful to their understanding and inquiry, but, somewhat torn, I allowed that they were entitled to skip questions they did not feel were useful.

The most consequential event of the day was Camille's discovery. In charging an electrophorus, she noticed that if she held it very close to the charged foam plate, when she touched the electrophorus with her finger the foam plate would lift off the table, as shown in Figure 4. Penny and Joanne were skeptical, but Camille was adamant. She called me and other students to their table to see it. With me holding the electrophorus, she demonstrated the effect several times, convincing us it was real. Camille was very excited and was as annoyed as I that the event was not recorded on videotape ("Sure, the day I make this great discovery, and the videocamera wasn't even on!"). Using her last name, I dubbed it the *Marino phenomenon*.

This was one of the discoveries that the worksheets intended. A question in Section 4.1C asked students to notice the attractive force between the electrophorus and the foam plate, but it was not until later in the worksheets that the students were intended to explain why this happens. Planning for class the next day, I decided to focus on this as a topic of conversation. I thought it could serve in several ways: It was another opportunity to show the students that their discoveries mattered, it was an example of a phenomenological contribution to scientific progress, and it was a phenomenon that could point us toward the notions of induced polarization and charging by induction.

March 12: The Marino phenomenon and the HAM theory. We had only half of the period for discussion on Friday because the class was to be released to allow students to visit the school science fair. We spent a moment to hear reports from students who had built electroscopes from soda cans and foil, using plans from

the worksheets I had assigned as homework. Several had charged their electrophores by rubbing their feet on the carpet, combing their hair, or touching a television screen.

We then turned to the Marino phenomenon. I demonstrated it, after Camille declined, and asked for explanations. Most of the discussion concerned whether the electrophorus plate already had a charge before I touched it with my finger. Bruce had an idea for a test: He asked me to neutralize the electrophorus and press it against the charged foam plate. We saw a weak attraction, not strong enough to lift the foam plate, but we were undecided what that implied.

With little time remaining, I asked Amelia, Ning, and Joanne to review their respective contributions to the charge separation model. Amelia's notion was that charge is not created but separated, Ning's was that the charges involved are the positive nuclei and negative electrons that they had learned make up atoms, and Joanne's was that different materials have different tendencies to accept or give up electrons. We dubbed these ideas the HAM theory, using the first letters of their last names, and students who had tested its predictions reported tentative confirmation. I then announced there would be a quiz the following week and allowed those who were interested to go to the science fair. About half of the class chose to stay, and they worked and played in various ways: Ricky experimented with his soda-can electroscope; Sean and Scott tried to catch up; Jean and Amelia suspended a neutral electrophorus and a charged foam plate by strings to find a weak attraction that became stronger when they touched the electrophorus.

March 18: A HAM explanation of the Marino phenomenon and some alternatives. We did not meet again until Thursday, March 18, because of snow days and a holiday. That class we intended to spend reviewing for the quiz, which would be on Friday; as it happened, we spent most of it talking about the Marino phenomenon.

Amelia, Ning, and Joanne presented explanations in line with their HAM theory. Ning's version was the most detailed and closest to a physicist's: The electrophorus starts out neutral, that is, with an equal amount of positive and negative charge. When it is near the negatively charged foam, negative charge is repelled toward the top of the electrophorus, and positive charge is attracted to the bottom. Touching a finger to the top of the electrophorus, Ning explained, would provide a way for the repelled negative charges to leave the plate, leaving behind a net positive charge. Having a positive charge, the electrophorus would attract the negatively charged foam plate more strongly, lifting it off the table.¹¹

¹¹Ning was careful to specify that the negative charges (electrons) are mobile, and the positive charges (atomic nuclei) are not. This was something the rest of the class had not established, and at this point, we still spoke generally of negative or positive charges moving.

Several students disagreed with this explanation. Steve, Susan, Bruce, and Sean all raised questions about the model, contesting the idea that the electrophorus plate could be charged one way on top and another way on the bottom. They seemed to think of charge as a property of the object as a whole, so they were troubled by an account of different parts of the electrophorus having different charges. In retrospect, this was consistent with some of what I had heard from students during group work, including around the “same material” explanation of charge sharing.

Standing at the front of the room, I tried various experiments that the students suggested, and along the way, we happened on another visually impressive phenomenon. Steve had suggested an experiment that required us to start with a neutral electrophorus. The electrophorus I was using had a foil-covered straw attached, and, to verify that it was neutral, I touched the foil straw to a pith ball. The pith ball did not respond, confirming that the electrophorus was neutral. Before proceeding with Steve’s experiment, however, I showed that I could make the pith ball respond to the straw by bringing a charged foam plate close to the bottom of the electrophorus plate, as shown in Figure 5: When I brought the charged foam near the bottom of the electrophorus and touched the foil straw to the pith ball, the pith ball repelled away. But, when I moved the foam plate away, the pith ball settled back. I moved the foam plate near and away several times, and we watched the pith ball respond in synch.

To the HAM authors and adherents, this behavior was consistent with their account of the Marino phenomenon: Brought close, the negatively charged foam plate attracts positive charge to the bottom of the electrophorus and repels negative charge to the top and onto the foil-covered straw. The pith ball, touching the straw, picks up a small negative charge itself and repels away. Moving the foam plate away allows the charge on the electrophorus to distribute evenly again, so that there is no longer a negative charge on the straw, and the pith ball is no longer repelled.

To Steve and the others, the repulsion of the pith ball suggested that the electrophorus plate was becoming charged or acting as a conduit of charge, by virtue of the proximity of the foam plate. I felt that “It was nice [that] it was Steve” (daily journal, March 18) who took the lead in arguing this view, which we would eventually decide was incorrect, because most of the class considered him the top student. Steve thought that the charge from the foam plate would “kinda like pass through” the electrophorus to affect the pith ball, “but it doesn’t stay [there], so when you move the foam away, it’s not there anymore. But when you touch it, you allow it to kinda like stick.”

Susan had it as a “spark” jumping between the two plates the way, she said, charge can “jump” across the “small space to another nerve” in a synapse. Sean called it a “current,” apparently, as had Greg, trying to connect what was happening to what he knew about a “complete circuit.” Bruce used the words

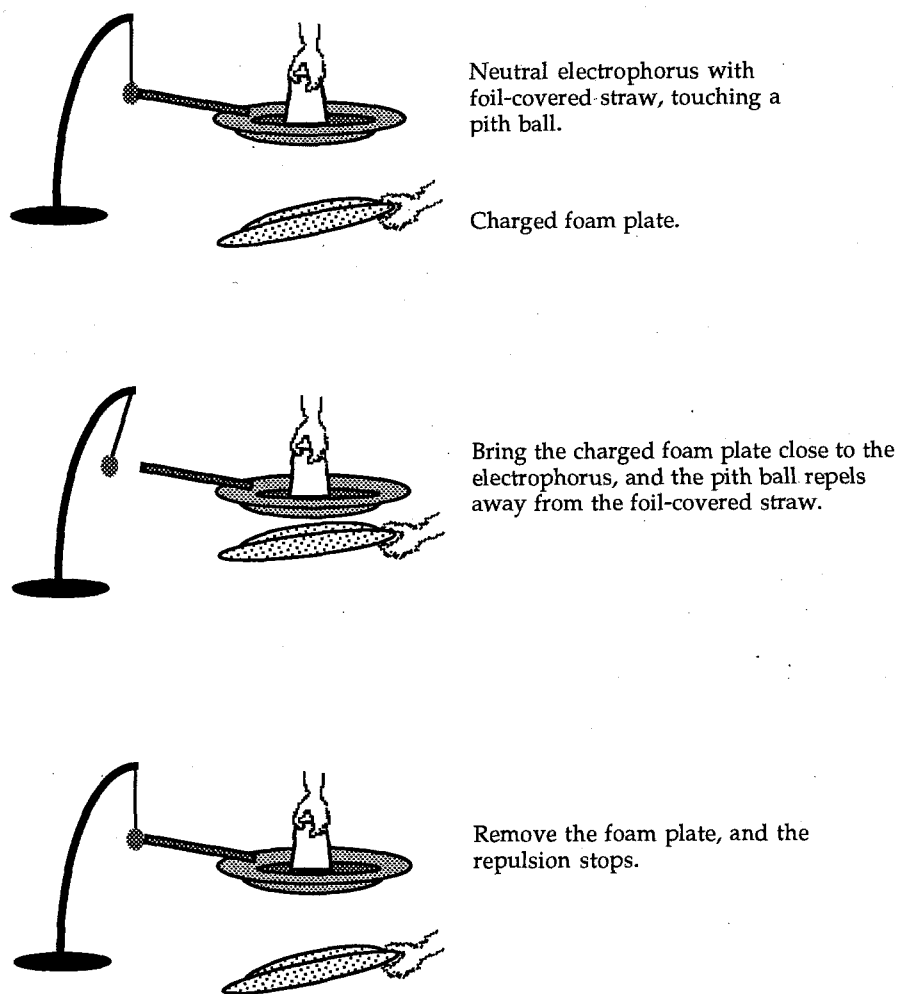


FIGURE 5 The phenomenon we discovered in class on March 18.

aura and *force field*. I was pleased these students were looking for connections and ideas from other phenomena, but I was daunted by the very different notions they were expressing about charge and current. At the same time, I wondered whether some of what they were saying might serve as seeds for the physicist's concepts of an electric field or an electric potential.

We drew depictions of the competing accounts on the blackboard, with the HAM charge-separation model on the left and the charging-by-proximity model on the

right. Toward the end of the period, the students identified a serious problem with the latter: If the foam plate was somehow sharing its charge with the electrophorus, the two plates would have the same charge and should repel each other, but we knew, from the Marino phenomenon and from Jean and Amelia's experiments suspending plates by strings, that they attract.

Ning had an idea for an experiment that she felt could confirm the HAM account: Proceed as usual in charging the electrophorus, but instead of touching it with my finger on the top, touch it on the bottom. Because the charge on the bottom of the electrophorus is the opposite of the charge on the top, she reasoned, touching the electrophorus on the bottom should have the opposite effect from touching it on the top. Whereas touching it on the top would provide an escape route for the negative charge repelled there, touching the bottom should provide an entrance for more negative charge to come onto the electrophorus, attracted by the positive charge on the bottom of the plate. Then the electrophorus would have a net negative charge, the same as the foam, and the two plates should repel.

I was both impressed by Ning's reasoning and worried that the outcome of her experiment would have the effect of disproving her correct explanation of charge induction. Her reasoning was clear and compelling, which was a virtue and a problem, because I doubted the experiment would come out as she predicted. I did not have the moment I needed to pin down for myself why I doubted her prediction or, more important, to figure out whether the students would be able to reconcile this counterevidence, given what they knew at the time.

We proceeded with the experiment, despite my hesitancy, and the plates still attracted, against Ning's prediction. Several students, especially Amelia, complained that I had not touched the plate on the bottom, that my fingers were not thin enough to reach underneath the electrophorus, because it was so close to the foam. I commented that we would need to think further about this experiment and that we had not resolved the debate between the HAM and proximity explanations. As class ended, I decided and alerted the students that one question on the quiz would ask them to defend a position in this debate.

After class, I settled my own understanding of Ning's experiment, but my reasoning depended on ideas we had not yet developed in class. It took me longer to construct a line of reasoning based only on what the students had seen and discussed.¹²

¹²The following week, Steve, Nancy, and Amelia modified Ning's experiment. They cut a small hole in the center of the foam plate and reached up through it to touch the bottom of the electrophorus. The results were the same as we found in class: Whether they touched the electrophorus on the top or on the bottom, it wound up with a positive charge. Amelia felt this disproved her explanation; Steve and Nancy were unsure. I offered them my explanation of why the result was not inconsistent.

March 19: The quiz. There were three essay questions on the quiz. Two were fairly short, asking students to explain two demonstrations that I presented during the quiz, each distinct from but related to phenomena they had explored. The third question began with a brief summary of the two sides of the previous day's debate and then asked:

Argue for your position, supporting what you say with evidence from the electrostatics labs. Be sure to address counter-arguments: What would people on the other side say, and what do you argue is wrong with their reasoning? If you can, devise an experimental test and explain how that test would distinguish between the two theories.

The quiz results were encouraging with respect to the students' understanding of electrostatic charge, attraction and repulsion, and conduction and insulation; the results were somewhat less encouraging with respect to their abilities to present arguments and evidence in defense of their position. In particular, many of the students still had trouble recounting a line of reasoning alternative to their own and identifying its flaw.

Our work with the Electrostatics Activities continued through the end of March, studying Leyden jars (capacitors) made from 35 mm film canisters and the motion of charge using bulbs sensitive to very small currents. The Marino phenomenon remained a relevant topic of discussion, and we eventually arrived at a consensus for the HAM explanation of an induced separation of charge. In April, a student teacher took over, and the class studied circuits, including electric potential, current, and resistance.

An Emergent Curriculum

Most teacher perceptions are of the sort presented in the first portion of this narrative: They concern and inform teacher interactions with individuals and groups, assessing and supporting their progress with respect to a general agenda. Often, however, teacher perceptions and judgments reshape that agenda, sometimes for individual students and sometimes for the class as a whole. The HAM theory, the Marino phenomenon, and the experiments and debates they engendered were examples, products of students' inquiry that I perceived and promoted as contributions to the substance of the course. In other words, I discovered student ideas that I chose to elevate to the level of curriculum.

Much of what the students discovered in these classes was directly in line with the design of the Electrostatics Activities worksheets, including both the HAM theory and the Marino phenomenon. Students do sometimes see and invent what they are intended to see and invent, and well-designed materials can improve the

chances of that happening. Materials such as Electrostatics Activities do not determine the flow of learning and instruction, but they can do much to productively constrain it, guiding students' experiences of the natural world. Thus, students following these worksheets are both likely to discover an attraction between the charged electrophorus and foam plate and highly unlikely to discover a repulsion. If it is an error to believe that truth resides in nature,¹³ it is also an error to believe that scientists' or students' constructions are independent of nature.

Still, the students' discoveries in these lessons often came on a different schedule from that guided by the materials. Amelia concocted charge separation in answer to a question designed to elicit that idea, but Camille discovered the Marino phenomenon at a moment when the worksheets would have had her thinking about something else, and the charging-by-induction explanation of the electrophorus was not expected until later. Moreover, much of what they discovered was neither guided nor anticipated. Nothing in the worksheets, for example, addressed either the "same material" or "by proximity" explanations of charge sharing; conceptions of charge as "current," as "aura," or as necessarily uniform throughout an object; or Ning's clever but flawed experiment of touching the electrophorus from underneath.

On a traditional view of teaching and curriculum, one might expect these worksheets to succeed in guiding the flow of student learning through the predetermined sequence of ideas and observations. Thereby, one would see shortcomings in the Electrostatics Activities for not anticipating the various aspects of students' knowledge and reasoning. The teacher's role in that view is peripheral, to help keep the students on the planned path, and the most successful materials should obviate teacher intervention.

On the view of teaching and curriculum that I am promoting, a curriculum succeeds not by guiding the flow of learning and instruction but by helping to establish an arena of activity rich with opportunities for student and teacher discovery. Within that arena, the substance of the course—the curriculum—emerges. This is a view of teaching that is more flexible with respect to pace and substance, but it is also more dependent on teacher awareness and judgment. Presuming uncertainty, the teacher does not expect students to arrive at given insights at given moments; rather, it is the teacher's responsibility to recognize when and if they arrive at those insights or others, to discover their progress, and to diagnose their difficulties. The teacher's role is not simply to keep students on the

¹³I say *if* here because many productive scientists claim to operate by precisely this belief. It would be strange to assert that they are simply incorrect, as if it is a normative truth that there is no normative truth. If the notion that truth resides in nature is a social construction, so is the notion that truth is a social construction. Which of these notions is valid should, like other social constructions, depend on context. In the contexts of many scientists' careers, it seems to have been effective for them to believe the former.

right path; it is to find out what paths there are, to scout ahead to see where they may lead, and to make judgments about which ones to follow.

That judgment often involves negotiating the tension between inquiry and traditional content. At the end of the period on March 10, the class had arrived at the HAM theory, and I had to decide how to proceed. One possibility was to endorse the account as correct, to mark a point of closure. Had it been closer to the end of the year, or had I been preparing the students for an achievement test, that is likely what I would have done. But I did not want to do anything that might support authority-centered beliefs about learning (Hammer, 1994). I also saw an opportunity to pursue an inquiry-oriented agenda. Instead of closing the subject, I tried to keep it open, to use it as a means to engage students in practices of reflecting on the model as a model, assessing its consistency with what else they knew, and looking for alternative explanations that might compete with it.

During the discussion on March 18, the HAM theory was hotly contested, with perhaps half of the students in the class disbelieving the correct charge separation account of the electrophorus. At the close of that period, I saw Ning's experiment as a lovely innovation that would likely lead students to a wrong conclusion. In each case, I had to decide how to coordinate inquiry and traditional content, although, again, the two agendas were not entirely distinct: The inquiry I wanted to promote would also, I hoped, help the students build more robust understandings of the traditional content I wanted them eventually to accept.

Again, too, there was much that I did not perceive. In reflecting, for example, on Steve's and others' contentions on March 18 that the electrophorus acquired a charge by the proximity of the foam plate, I now realize that they were correct in a way I did not recognize at the time. The definition posited by the worksheets in Section 1.2 stated that an object is charged if it "attracts bits of paper"; by that definition, the students were correct. The worksheets prompted some revisions to that definition in Section 2, but none that would affect the correctness of this view. In arguing that the electrophorus was not charged, Ning and the others were implicitly changing the definition. Had this occurred to me at the time, I would have made a focus of discussion, in the context of this disagreement, our definition of *charged* and how we should revise it. This might have had the benefit both of helping the students develop an appreciation of how definitions form and become revised and of helping them arrive at a more appropriate definition. As it happened, that substance did not emerge as part of our curriculum because I did not perceive it in the discussion.

TEACHING FROM A STANCE OF INQUIRY

The image of teaching presented in this article should be distinguished from *teacher research* or *action research* as described, for example, by Cochran-Smith and Lytle

(1993) and by Feldman (1996). In particular, what I have characterized as discovery teaching is teaching from a stance of inquiry, that is, everyday teaching and everyday inquiry, which is rarely systematic, articulate, or made public. This by no means questions the value of teacher research; rather, it focuses on the inquiry of teaching in and of itself, independent of any objectives of description or argumentation.

To a teacher adopting such a stance, the classroom is an arena not only for student exploration but also for teacher exploration—of the students' understanding and reasoning, of the subject matter, of what constitutes progress toward expertise, and of how to facilitate that progress. This entails a shift in the teacher's conception of planning, in that it is planning for exploration rather than to achieve a set of predetermined, observable outcomes. It also entails a shift in the role of materials—as helping to shape an arena of activity rather than as directing the flow of learning and instruction. Finally, it entails a shift in the understanding of the substance of the course—as flexible and evolving in response to perceptions of the students' strengths and weaknesses rather than fixed in advance by a syllabus.

Student Inquiry and Traditional Content

This stance of inquiry, as opposed to the conventional stance of certainty (McDonald, 1992), changes, in several respects, how a teacher experiences and negotiates the tension between student inquiry and traditional content.

First and most simply, it affords flexibility and demands teacher judgment with respect to the pace and paths by which students meet traditional content-oriented objectives. Rather than keeping students on track and making appropriate discoveries on a designated schedule, the teacher's responsibility is to ascertain what they are discovering and to judge how to proceed. Students in the class described earlier, for example, arrived at an understanding of the difference between a conductor and an insulator later and by a more convoluted route than I or the materials had anticipated; they engaged the topic of charging by induction earlier and with less preparation.

Second, a stance of inquiry affords flexibility and demands judgment with respect to the pursuit and evolution of course objectives. Teacher perceptions of students' particular strengths and needs influence decisions of whether to foreground inquiry or traditional content-oriented objectives and of whether and how to modify them. Thus, at the outset of our work with Electrostatics Activities, I saw a need for inquiry-oriented intervention, to press the class into more productive use of the worksheets; on the day before the quiz, I gained new awareness of the students' reasoning about charge and the mechanism of the electrophorus, and it became part of my agenda to address the alternative ideas they expressed.

Third, a stance of inquiry affords flexibility and judgment with respect to the nature of inquiry and its relation to content. Rather than commit to a specific but inadequate definition, the teacher may adopt a more open, varied view of what constitutes expertise in the discipline and how it may develop in students, expecting that view to evolve. Thus Greg and Jean's "same material" explanation and experimental confirmation gave me fresh insight into how students' and scientists' inquiry may depend on and entwine with their traditional content knowledge. Considering the respectively theoretical and empirical contributions of Amelia's explanation and Camille's discovery renewed my sense of the range of ways in which students and scientists may enter and practice the discipline of physics.

The Intellectual Demands of Teaching

It is important to recognize that this view of the coordination of inquiry and traditional content places substantial intellectual demands on the teacher.

The students' arguments on March 18, for example, challenged me to understand what they meant in saying the charge on the foam plate was passing through the electrophorus, or surrounding it like an aura, or jumping like a spark. Perhaps by *charged*, they meant something such as *electrostatically active*? Might there be a substantive connection between some of their ideas and physicists' ideas, perhaps between the student's notion of an aura and the physicist's concept of a field, or are the ideas fundamentally inconsistent?

These matters presented demands on my understanding and reasoning in physics. There were questions that I needed to solve for myself in these lessons, such as why a plastic straw could appear to conduct electricity, or what precisely was the flaw in Ning's reasoning for her experiment at the end of class on March 18. More than that, I needed to follow the students' arguments, to understand them on their own terms. Given what they knew and had experienced, were their inferences reasonable and self-consistent, or were they flawed in ways students should be able to recognize? What line of reasoning could I find, starting from the students' positions, that could lead them in the direction of the ideas I hoped they would develop? What might be seeds of expertise in their ideas and reasoning, and what might be impediments?

A teacher with inadequate preparation in the discipline would be at a substantial disadvantage in following students' unfamiliar arguments and ideas expressed in unfamiliar vocabulary (McDermott, 1990). This magnifies concerns about the practice of assigning teachers to courses outside their expertise. The notion that the teacher can "stay a chapter ahead" of the students is embedded in a view of substance as traditional content and in a stance of certainty regarding learning and instruction. Recognition of discipline-specific intellectual demands also raises questions about

current trends toward interdisciplinary teaching and teacher certification, to the extent that these require breadth of preparation at the cost of depth within a given area.

More generally, how teachers perceive and understand their students reflects the intellectual resources they have available for perceiving and understanding. These resources go beyond knowledge and reasoning in the discipline, as did the perceptions I have recounted in this article, including those of the students' initial fill-in-the-blanks approach, Julie's disengagement, Camille's pride in her discovery, or Steve's reputation as the top student in the class. What I perceived, in all these respects, reflected the resources I had available, and what I did not perceive reflected limitations. There was much I did not notice, including the earnestness of Sarah's and Nancy's ideas about the plastic straw and the fact that it was consistent with the definition in the worksheets to conclude that the electrophorus was charged by the proximity of the charged foam plate.

Teachers develop these resources in many ways, often through teaching. In these lessons, for example, I learned more about how the concepts of charge and current may not be distinct in students' reasoning, that students may consider the shape of an object such as a straw relevant to its conductivity, and that they may be confused over when to think of charge as a property of an object as a whole or when to think in terms of the distribution of microscopic charges. I will not be as surprised the next time I hear the "same material" explanation, and the next time I use worksheets, I will consider presenting them from the outset as tools students should use at their discretion.

Teachers who have the opportunity also develop resources through conversations with colleagues. When I present a videotape or transcript of one of my classes to others, they invariably notice things I have not. Different teachers perceive students' work and needs in different ways, and professional exchange supports teachers' development of their intellectual resources as they introduce and refine new ideas. Case-based (J. H. Shulman, 1992) methods of teacher education and professional development promote both individual reflection and collegial exchange.

A Role for Perspectives From Education Research

Teachers may also develop intellectual resources from reading, discussing, or participating in education research. In these classes, my understanding of the students' initial approach to the worksheets was influenced by perspectives on cognition as situated in social practices (J. S. Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991; Meira, 1991). My understanding of their reasoning about charge and current was influenced by perspectives on cognitive structure (diSessa, 1993; Strike & Posner, 1985; see also Hammer, 1996a). My perceptions of students

as having beliefs about knowledge and learning were shaped by my own research into students' epistemologies (Hammer, 1994; see also Hammer, 1995a). Perspectives on the history and philosophy of science (Feyerabend, 1988; Latour, 1987) moved me to adopt a more open view of the nature of scientific inquiry in scientists and as it might appear in students (see also Hammer, 1995b). This is not to suggest that I have incorporated these perspectives into an encompassing, coherent theory of learning and instruction; I have not. Rather, I am constructing a collection of interpretive lenses, or conceptual tools, based on or inspired by these perspectives and others, that serve me variously as I try to make sense of what happens in my classes.

My purpose here is not to present a taxonomy of forms and sources of teachers' intellectual resources but to suggest a conceptualization of how education research might contribute to instructional practice (Hammer, 1996b). On a traditional view framed by assumptions of certainty, research produces methods, curricula, and principles of learning and instruction, which teachers adopt and apply. A more progressive view focuses not on communicating results of research to teachers but rather on teachers' participation in that research (Cochran-Smith & Lytle, 1993; Feldman, 1996). The latter can be more accommodating to assumptions of uncertainty because it can locate the research and its implications in the situation.¹⁴

I am suggesting a view of research, whether by teachers or by researchers, as contributing to instructional practice by supporting and enhancing teacher inquiry, not necessarily by imposing on that inquiry an esthetic of research or by providing a theoretical foundation but by providing ideas to support teachers' construction, articulation, and refinement of intellectual resources. A perspective from research may provide a framework and vocabulary to help teachers become aware of, communicate, and develop their often tacit perceptions and judgment. Or, perhaps less often, it may lead teachers to entirely new perceptions and considerations.

McDonald (1986) offered a similar image in his account of the *ironic role* of educational theory in contributing to discussions among a group of teachers. The Teachers' Resources Network (Davenport & Sassi, 1996), from which I have drawn the term *resource*, was designed from a similar orientation toward the role of resources in teachers' practices, with resources broadly conceived to include curriculum materials as well as both theoretical and practical accounts of learning and teaching. Davenport and Sassi suggested that accounts that include narratives of authentic classroom learning and instruction are especially useful for teachers.

This view of the contribution of research to instructional practice suggests the importance of understanding how perspectives from research may influence teach-

¹⁴It is important to acknowledge, however, that teacher research may also be conducted and presented from a stance of certainty.

ers' perceptions and judgments. Hewson and Hewson (1988) and the Cognitively Guided Instruction project (Knapp & Peterson, 1995; Peterson, Fennema, & Carpenter, 1992) considered the implications of research on students' knowledge and learning in terms of its influence on teacher understanding. A group of physics teachers and I are working along similar lines to understand the influence of perspectives from education research on teachers' perceptions and judgments, in the context of collaborative inquiry into student participation, knowledge, and reasoning, using episodes from the teachers' classes.

Implications in a Culture of Certainty

Teaching, closely read, is messy: full of conflict, fragmentations, and ambivalence. These conditions of uncertainty present a problem in a culture that tends to regard conflict as distasteful and that prizes unity, predictability, rational decisiveness, certainty. This is a setup: Teaching involves a lot of "bad" stuff, yet teachers are expected to be "good." (McDonald, 1992, p. 21)

The view of teaching I have described in this article is not new. Many teachers practice discovery teaching, teaching from a stance of inquiry with respect to their students. But they do so against the cultural grain, against a set of assumptions and esthetics of predictability and control that remain embedded in practices at all levels of the educational system. I have focused on uncertainties regarding the substance of the discipline, specifically concerning the coordination of student inquiry and traditional content. In closing, I touch briefly on some implications of this view of teaching with respect to teachers' course loads, curriculum, teacher education, and the use of cases.

First, this article presented a highly distilled account of only 2 weeks from a single class, but most teachers are responsible for four or five classes a day. That teachers often have several sections of the "same prep" is little solace: As every teacher knows, different classes respond differently to the same lesson, and to embrace fully a stance of inquiry in teaching would be to surrender this notion of sameness. If schools are to conceive of teaching as involving inquiry, perception, and judgment, one implication is clear: Teacher loads must be reduced to make time for that inquiry.

A second implication is the need for a distinction between the curriculum in the sense of the syllabus and materials chosen in advance, and the curriculum in the sense of the substance and form of learning and instruction. To be sure, most teachers adapt materials to their situations, but there has been relatively little discussion of how this occurs or what it implies for curriculum developers.

Third, this view of teaching suggests an agenda for preservice teacher education: cultivating a stance of inquiry and helping prospective teachers develop intellectual

resources for pursuing that inquiry. This, a principal virtue of the use of cases (J. H. Shulman, 1992) in preservice teacher education, draws student teachers into practices of inquiry as well as into practices of professional exchange.

Finally, with respect to the use of cases more broadly, we need to learn more as a community about how to use cases (L. S. Shulman, 1992) and how to “read” teaching (McDonald, 1992) with all of its messiness, conflicts, and ambiguity. As I noted earlier, all instruction goes awry in at least some respect: There is always something that the teacher did not notice, or did notice but chose not to address, or tried to address but did not resolve. This presents a challenge to substantive critique of teaching, part of McDonald’s setup: One can always find reason to fault the teacher. But the solution is not simply to support all teacher decisions. Whether for the purposes of research, collaboration, or evaluation, we need to develop appropriate practices of criticism.

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REFERENCES

- Ball, D. (1993). With an eye on the mathematical horizon: Dilemmas of teaching elementary school mathematics. *Elementary School Journal*, 93, 373–397.
- Brown, A. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences*, 2, 141–178.
- Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher*, 18(1), 32–42.
- Cochran-Smith, M., & Lytle, S. L. (1993). *Inside/outside: Teacher research and knowledge*. New York: Teachers College Press.
- Davenport, L. R., & Sassi, A. (1996). Transforming mathematics teaching in grades K–8: How narrative structures in resource materials help support teacher change. In B. S. Nelson (Ed.), *Inquiry and the*

- development of teaching* (pp. 37–46). Newton, MA: Education Development Center, Center for the Development of Teaching.
- diSessa, A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, 10, 105–225.
- Feldman, A. (1996). Enhancing the practice of physics teachers: Mechanisms for the generation and sharing of knowledge and understanding in collaborative action research. *Journal of Research in Science Teaching*, 33, 513–540.
- Feyerabend, P. K. (1988). *Against method*. New York: Verso.
- Gagné, R. M. (1965). *The psychological bases of science—A process approach*. Washington, DC: American Association for the Advancement of Science.
- Hammer, D. (1994). Epistemological beliefs in introductory physics. *Cognition and Instruction*, 12, 151–183.
- Hammer, D. (1995a). Epistemological considerations in teaching introductory physics. *Science Education*, 79, 393–413.
- Hammer, D. (1995b). Student inquiry in a physics class discussion. *Cognition and Instruction*, 13, 401–430.
- Hammer, D. (1996a). Misconceptions or p-prims: How may alternative perspectives of cognitive structure influence instructional perceptions and intentions? *The Journal of the Learning Sciences*, 5, 97–127.
- Hammer, D. (1996b). More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. *American Journal of Physics*, 64, 1316–1325.
- Hewson, P. W., & Hewson, M. G. A. (1988). An appropriate conception of teaching science: A view from studies of science learning. *Science Education*, 72, 597–614.
- Hodson, D. (1988). Toward a philosophically more valid science curriculum. *Science Education*, 72, 19–40.
- Knapp, N., & Peterson, P. L. (1995). Teachers' interpretations of "CGI" after four years: Meanings and practices. *Journal for Research in Mathematics Education*, 26, 40–65.
- Lampert, M. (1989). Choosing and using mathematical tools in classroom discourse. In J. Brophy (Ed.), *Advances in research on teaching* (pp. 223–264). Greenwich, CT: JAI.
- Lampert, M. (1990). When the problem is not the question and the solution is not the answer: Mathematical knowing and teaching. *American Educational Research Journal*, 27, 29–63.
- Latour, B. (1987). *Science in action: How to follow scientists and engineers through society*. Cambridge, MA: Harvard University Press.
- Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. New York: Cambridge University Press.
- Lockett, G. (1996). Penumbra. In M. Shinohara, R. Wenn, & A. Sussman (Eds.), *Tales from the electronic frontier* (pp. 14–20). San Francisco: WestEd.
- McDermott, L. C. (1990). A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers. *American Journal of Physics*, 58, 734–742.
- McDonald, J. P. (1986). Raising the teacher's voice and the ironic role of theory. *Harvard Educational Review*, 56, 355–378.
- McDonald, J. P. (1992). *Teaching: Making sense of an uncertain craft*. New York: Teachers College Press.
- Meira, L. (1991). *Explorations of mathematical sense-making: An activity-oriented view of children's use and design of material displays*. Unpublished doctoral dissertation, University of California, Berkeley.
- Minstrell, J. (1989). Teaching science for understanding. In L. B. Resnick & L. E. Klopfer (Eds.), *Toward the thinking curriculum: Current cognitive research* (pp. 129–149). Alexandria, VA: Association for Supervision and Curriculum Development.

- Morse, R. A. (1991). *Electrostatics activities for students*. College Park, MD: American Association of Physics Teachers.
- National Research Council. (1996). *National science education standards*. Washington, DC: National Academy Press.
- Peterson, P. L., Fennema, E., & Carpenter, T. (1992). Using children's mathematical knowledge. In B. Means, C. Chelemer, & M. S. Knapp (Eds.), *Teaching advanced skills to at-risk children* (pp. 68–111). San Francisco: Jossey-Bass.
- Richardson, V. (1994). Conducting research on practice. *Educational Researcher*, 23(5), 5–10.
- Rosebery, A. S., Warren, B., & Conant, F. R. (1992). *Appropriating scientific discourse: Findings from language minority classrooms* (TERC Working Papers). Cambridge, MA: TERC.
- Roth, W.-M. (1995). Inventors, copycats, and everyone else—The emergence of shared resources and practices as defining aspects of classroom communities. *Science Education*, 79, 475–502.
- Roth, W.-M., & Roychoudhury, A. (1993). The development of science process skills in authentic contexts. *Journal of Research in Science Teaching*, 30, 127–152.
- Ruopp, R., Gal, S., Drayton, B., & Pfister, M. (1993). *LabNet—Toward a community of practice*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Sassi, A. M., & Goldsmith, L. T. (1996, April). *Beyond recipes and behind the magic: Mathematics teaching as improvisation*. Paper presented at the annual meeting of the American Education Research Association, New York.
- Schifter, D. (1996). *What's happening in math class? Vol. 1. Envisioning new practices through teacher narratives*. New York: Teachers College Press.
- Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. New York: Basic Books.
- Shulman, J. H. (1992). *Case methods in teacher education*. New York: Teachers College Press.
- Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review*, 57, 1–22.
- Shulman, L. S. (1992). Toward a pedagogy of cases. In J. H. Shulman (Ed.), *Case methods in teacher education* (pp. 1–30). New York: Teachers College Press.
- Strike, K. A., & Posner, G. J. (1985). A conceptual change view of learning and understanding. In L. H. T. West & A. L. Pines (Eds.), *Cognitive structure and conceptual change* (pp. 211–231). New York: Academic.
- Warren, B., & Rosebery, A. S. (1996). "This question is just too, too easy!" Perspectives from the classroom on accountability in science. In L. Schauble & R. Glaser (Eds.), *Innovations in learning: New environments for education* (pp. 97–126). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.
- Wilson, S. M., Shulman, L., & Richert, A. (1987). "150 different ways" of knowing: Representations of knowledge in teaching. In J. Calderhead (Ed.), *Exploring teachers' thinking* (pp. 104–124). London: Cassell.
- Wilson, S. M., & Wineburg, S. S. (1993). Wrinkles in time and place: Using performance assessments to understand the knowledge of history teachers. *American Educational Research Journal*, 30, 729–769.
- Wineburg, S. S., & Wilson, S. M. (1988, September). Models of wisdom in the teaching of history. *Phi Delta Kappan*, 70, 50–58.

APPENDIX A

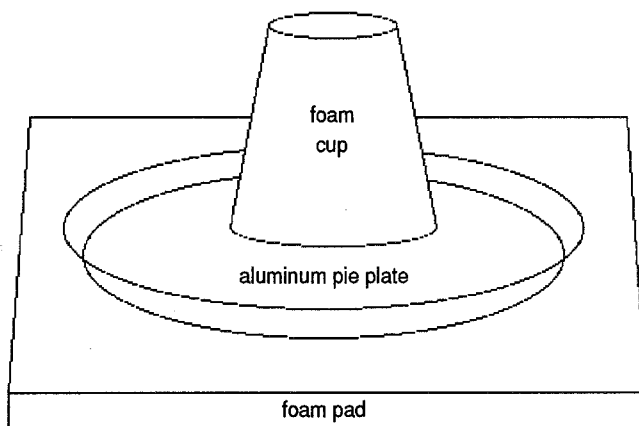
Morse (1991) Section 4

Section 4. The Electrophorus: A Device for Generating Static Electricity

Materials: Dow blue styrofoam insulation or styrofoam picnic plate, 8 or 9 inch disposable aluminum pie plate, foam coffee cup, plastic drinking straw, wool or fur, and tape.

4.1

A. To make an electrophorus, take a 30 cm (one foot) square of foam for the base, or use a disposable styrofoam picnic plate. Take a disposable aluminum pie plate (8" or 9") and fasten an insulating handle to it by taping a styrofoam cup upside down in the center of the pie plate. You will also need to make a second pie plate with a foam cup handle for some of the experiments, or you may share equipment with a partner.



B. Rub the top surface of the foam with fur to charge it. Slowly lower the electrophorus pie plate (henceforth called the electrophorus plate) to a height of a few millimeters above the foam while holding it by the cup handle. Be careful not to touch the pie plate with your hand or arm unless instructed to do so.

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Still holding the electrophorus plate by the cup, raise it away from the foam. Touch the electrophorus plate to your leaf electroscope. Is the electrophorus plate charged?

C. Again lower the electrophorus plate to a point just above the foam, and this time touch the electrophorus plate briefly with your finger while it is on or just above the foam. What happens?

Slowly lift the electrophorus plate by the handle. Do you feel any interaction between the electrophorus plate and the foam pad as you lift? Is it attractive or repulsive?

Touch the electrophorus plate to your leaf electroscope. Is the electrophorus plate charged?

Touch the electrophorus plate to your pith ball. What does the pith ball do? What can you say about the charge on the pith ball and the charge on the electrophorus plate.

Now bring the foam pad near the pith ball. What can you say about the charges on the pith ball and the foam pad?

Clearly the electrophorus is an effective, interesting and slightly puzzling charging device. Temporarily you will use it to supply charges for other experiments before trying to develop a better understanding of how it works.

4.2

A. Take a plastic straw and glue aluminum foil to it so that it is covered with foil. Take another straw without a foil covering. Use a bit of duct or masking tape and tape one end of each straw to the rim of the electrophorus plate at separate places so that they stick out horizontally. Set up the pith ball electroscope and briefly touch the pith ball with your finger. Rub the foam pad or the foam plate with the wool or fur, then pick up the electrophorus plate by its handle, set it on the foam pad and touch it briefly with your finger. Lift the electrophorus plate by its handle, being careful not to touch the plate or the straws. Move the plate so that first the

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outer end of the plain straw touches the pith ball and then the outer end of the foil straw touches the pith ball. What happens in each case?

Does the plain straw charge the pith ball?

Does the foil straw charge the pith ball?

Is the end of the plain straw charged?

Is the end of the foil straw charged?

How could you find out if the charged state of the pith ball is the same as or different from that of the styrofoam? Devise an experiment and find out.

B. Repeat the experiment in 4.2A, this time using the foil leaf electroscope. Does it move when touched with the plain straw? With the foil straw?

C. How did the foil covered straw get charged? How did the pith ball get charged? How is this different from the way that the tapes and foam got charged?

4.3

Rub the foam pad with the fur or wool again, then pick up the electrophorus plate by its handle, set it on the foam pad and touch it briefly with your finger. Lift the electrophorus plate by its handle, *being careful not to touch the plate or the straws*. Now touch the end of the plastic straw with your finger and then bring the electrophorus plate near the hanging pith ball. Is the plate still charged? Did touching the end of the plastic straw change the charge on the plate?

Repeat the charging sequence. This time touch the end of the foil covered straw briefly with your finger. Bring the electrophorus plate near the pith ball. Is the plate still charged? Did touching the end of the foil covered straw change the charge on the plate?

Objects that behave like the plastic straw, the foam and the tape are called insulators. Objects that behave like the foil covered straw and the pith balls are

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called conductors. We will continue to look at the differences in their behavior and try to account for it in developing a model of electric charge. In a conductor we may imagine that one or both types of charge are free to move, whereas in an insulator neither type of charge can move very much or very readily. You may now use the electroscope and electrophorus to investigate a variety of materials and see if they behave like conductors or insulators. You will probably find that some materials have a behavior in between those of the foil covered straw and the plastic straw, and that there is a range of behavior of materials.

4.4

Can you explain the results of experiments 4.1, 4.2 and 4.3 using this model? Sketch a sequence of diagrams like a comic strip showing what might be happening to the charges in these experiments. Check your description with your teacher.

APPENDIX B

Brief Explanations of Some Electrostatic Phenomena

Peeling Tapes

The second section of Morse's (1991) worksheets involves transparent adhesive tape. Peeling tape, in particular, is an effective way of generating a static electric charge.

One of the activities was as follows: Cut two pieces of tape, each about 6 in. (15 cm) long. Stick one piece of tape to a table top, and stick the second piece on top of the first, to make a pair. Then, keeping the pair together, peel them from the table top. For this activity, you want the pair to be electrostatically neutral, but peeling them from the table probably gave them a charge. To neutralize them, brush both sides of the pair with your fingers, or, better, brush them against a metal water faucet.

With the pair neutral, peel them apart, with one quick pull. This should give the two pieces of tape an equal but opposite electric charge, so that they attract each other. If you charge other objects, such as other pieces of tape, plastic straws or Styrofoam™ plates, they will all attract one piece of tape from the pair and repel the other. This suggests that there are two kinds of electric charge, which have come to be known as *positive* and *negative*. Positive charges repel each other and attract negative charges; negative charges repel each other and attract positive.

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The Pith Ball

A pith ball is a tiny ball used to detect electric charge, so named because they were traditionally made from pith (the inside of a plant stem). For these activities, we often used tiny pieces of crumpled aluminum foil instead of pith. This ball becomes charged by contact with other charged objects; once charged, it is visibly attracted to the opposite charge and repelled by a like charge. In this way, it is useful for detecting the presence of electric charge.

Induced Polarization: Why a Charged Electrophorus Attracts a Neutral Pith Ball

Greg and Jean spent much of their time on March 8 trying to understand why a charged electrophorus would attract a neutral pith ball. To a physicist, the answer is this: At first, the pith ball is neutral, which means it has the same amount of positive and negative charge. But the positively charged electrophorus causes a *polarization* of charge in the neutral pith ball, pulling negative charges to one side of the pith ball and repelling positive charges to the other, as shown in Figure 2. This means that the negative charges in the pith ball are closer to the electrophorus plate than are the positive charges in the pith ball, so the negative charges are attracted slightly more strongly than the positive charges are repelled. In this way, there is a net attractive force by the electrophorus on the pith ball. When the pith ball strikes the plate, however, charge can move between the plate and the pith ball, and the pith ball ends up with more positive charge on it than negative. The greater positive charge on the pith ball is repelled more strongly than the negative charge is, so the net force on the pith ball becomes repulsive.

More Induced Polarization: Charging the Electrophorus

A neutral object has an equal amount of positive and negative charge (protons and electrons). Rubbing a foam plate with cloth or fur causes it to have a surplus of negative charge. That is the first step in charging an electrophorus: Charge a foam plate. The next step is to bring the electrophorus, an aluminum plate, near the charged foam plate, as shown in Figure B1. With the electrophorus plate close to the charged foam, the negative charge on the foam repels the negative charge in the electrophorus and attracts the positive charge. Aluminum *conducts* electricity, which means that (negative) charge can move within it, so the repulsion of the negative charge by the foam plate pushes some negative charge to the top of the electrophorus. This gives the top of the electrophorus a net negative charge and leaves the bottom of the plate with a net positive charge, as shown in Figure B2. Because no charge moves onto or off the electrophorus, however, it remains neutral

as a whole, with equal amounts of positive and negative charge. The final step, then, is to touch the top of the plate with something that will conduct electricity, such as a finger, as shown in Figure B3. Touching the top of the electrophorus gives the negative charge there an escape route—a way to move even further from the negatively charged foam plate—and there is a small spark between the plate and the finger as this happens. This reduces the amount of negative charge on the electrophorus, leaving it with a net positive charge.

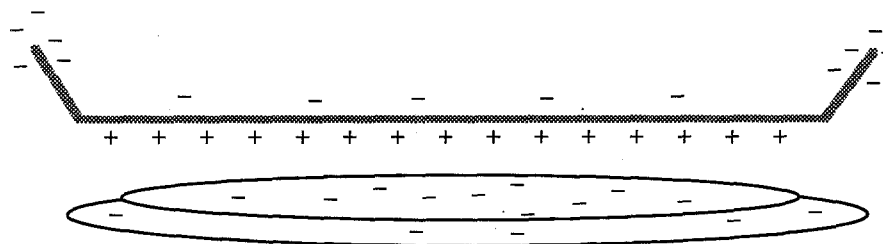
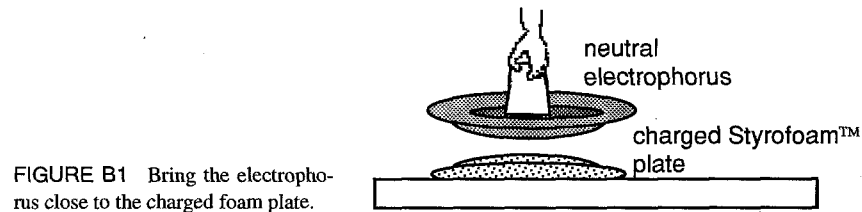


FIGURE B2 The negatively charged foam plate attracts positive charge in the electrophorus and repels negative charge. Because the electrophorus is made of aluminum and allows (negative) charge to move, the aluminum plate becomes polarized, with more negative charge on the top and more positive charge on the bottom.

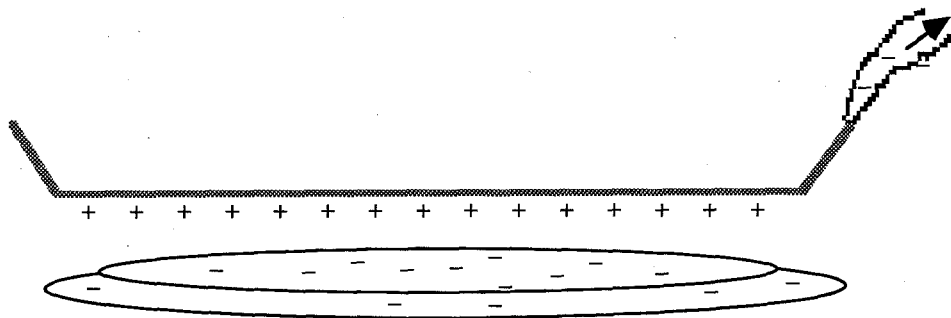


FIGURE B3 Touching the electrophorus with a finger lets repelled negative charge leave the plate, leaving it with a net positive charge.