Experimenting with magnetism: Ways of learning of Joann and Faraday

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This paper narrates learning as it evolved through experimental work and interpretation in two distinct investigations: the explorations of permanent magnets and needles conducted by a student, Joann, as I interactively interviewed her, and Faraday's initial experimenting with diamagnetism, as documented in his *Diary*. Both investigators puzzled over details, revisited their confusions resiliently, and invented analogies as ways of extending their questioning; ''misconceptions'' and conflict were not explicit to their process. Additionally, Faraday formed interpretations—and doubts critiquing them—that drew upon his extensive experience with magnetism's spatial behaviors. These two cases suggest that physics instruction could include opportunities for students' development of their own investigatory learning.

I. INTRODUCTION

In this paper I narrate portions of the evolving engagement of two learners through their questioning and experimenting with magnetism. One, Joann, was an undergraduate whom I interactively interviewed while she experimented with permanent magnets and sewing needles. The other, Michael Faraday, recorded his experimenting and thinking in an extensive diary; here, I follow entries made during his initial discovery of diamagnetism in November 1845. Passages were selected from the larger body of both investigators' work to convey the developing of understanding of a physical consistency: Joann worked out consistency in the pushing apart and pulling between ends of magnetized needles, Faraday described the force law associated with a bismuth sample's motions. I suggest the fuller complexity of what happened and of the investigators' thinking, along with continuities in what they did and their ways of learning, by excerpting some preceding work.

The settings through which these narratives of learning evolved are unlike what most physics teachers and students experience. What happens in classrooms is bounded in many ways. Yet openings to questioning and change of that practice can arise through looking not only at what occurs under those familiar constraints, but also at what can be possible for learners engaged in wondering about physical things. Through reflecting upon such examples of learning, we may become sensitive to evidences of, or beginnings for, questioning in any student's responses to phenomena. Perhaps with such study we can see how ways of deepening and extending students' thinking and experience with physical phenomena are not so remote, the barriers to it not so substantial, and that this work can uncover and extend what we know.

Within the narratives, notice of details in what they do and of what happens with materials motivates the further questioning of Joann and Faraday. In ways original to each investigation, the work is often initiated through playful curiosity; it proceeds by developing methods for testing ideas and inventing analogies to other examples. There are, of course, differences in how Joann and Faraday work that do not only originate in their disparate circumstances. These derive from differences in their experience and the depth of their conviction, developed through that experience, that natural phenomena evidence (often invisible) consistencies. For example, while Joann was often reluctant to make inferences that went beyond her evidence, Faraday did that by employing both doubts about his understandings, and certainties about how nature works.

Faraday's work at making sense of new evidence differs from Joann's spontaneous responses to her experimenting. He researched the spatial properties of diamagnetism to both challenge and extend his already evolving field interpretation. Joann did not record her evidence, thus some of her confusions and the incompleteness of it were not accessible to her, to shape and challenge her further experimentation and thought. Yet it is through these investigatory activities with magnets that she formed her own understandings of natural consistencies. Her developing understandings are not, then, disjoint from Faraday's engagement with natural consistencies, which deepened throughout his extensive experience.

A. Interviewing studies of individual students learning physics

We interact with phenomena to understand more about them; this paper documents and explores how such interactions extended Joann's and Faraday's understandings of magnetic phenomena. I studied ongoing phenomena of learning empirically through direct interaction with Joann and indirect interpretation of Faraday's records. My interactions with Joann were conducted through the method of extended clinical interviewing. Prior studies have used other techniques of interviewing individual physics students to get beyond or augment[1] the limited data available from exam scores and questionnaires. While interviewing protocols may be specific to an educational research project's intent, projects involving interviews with over 100 students,[2] or more,[3] as well as single case studies,[4] have produced data and analysis provocative for the instruction of physics.

1. Misconceptions interviewing

Some interview studies are designed to extract commonalities from students' use of physical explanations. Each student is asked to predict the outcome of the same demonstration or problem. Students' explanations are compared with each other and with explanations they were expected to learn from instruction before being interviewed: common (and incorrect) traits are regarded as evidence for students' underlying misconceptions about physical things.[5] For example, physics students were asked to compare relative speeds of two objects moving in a demonstration which they observed, but could not manipulate. Most said that objects' speeds were the same at the moment when their positions coincided. The students' kinematical misconceptions (regarding position and speed) were identified from these responses.[3] The researchers consider that such misconceptions are generalized characteristics of students' preinstructional state, which resist change during ordinary instruction.

Such interviews are not viewed as episodes of learning in themselves. In fact, any learning occurring during an interview would disrupt the researcher's intent of characterizing common states of understanding.[6] Such studies also do not look for, or retain evidence of, students' novel efforts and how initial ideas provide students with a means for working toward more developed ideas. Transcript excerpts are selected to illustrate typical, not distinctive, responses.

Although learning is not studied, the misconceptions analysis derived from these interviews informs the design of models for instruction through which students are to overcome their misconceptions. Such models often seek to change students' ideas through introducing explicit conflict between those ideas and contradictory evidence or explanations. These models assume that once students recognize their ideas are wrong, they will adopt more correct ones.[7]

2. Observation and clinical interviewing

Other studies use interviewing to explore how physics students go about learning or thinking. Each interviewee may participate in multiple distinct and evolving sessions.[8,9] Topics discussed and questions asked may arise spontaneously during an interview, and include problems assigned in the student's class.[10] These interviewers adapt observational and clinical practices used in psychology. For example, the interviewer may observe students' work, form inferences from what students say, and experimentally test, or follow, those inferences in subsequent questioning.[11]

Noting what students say or do within the process of their discussion or work on tasks, these studies analyze interview details for evidence of students' methods, intuition, and beliefs. Interviewed students—and experts who were also interviewed—reason about new problems by using nonformal methods, including inventing analogies to other examples.[10,12] These researchers document how students produce explanations, not from misconceptions that they hold statically, but through their developing adeptness in using primitive understandings of phenomena.[8] The beliefs students have about how physical knowledge is produced have also been shown to influence students' learning.[9]

Interview evidence from such studies has motivated critical alternatives to misconceptions accounts. These critiques dispute the use of scientific models in framing what misconceptions are, the consistency ascribed to students' holding of misconceptions, and the assumption that students' misconceptions are changed only through a process of conflict. Instead, they provide examples to argue that students' preexisting ideas form beginnings for transitions to new understandings and that expertise evolves through continuity with initial ideas, not by their replacement, removal, or exclusion. They suggest narrative studies can document how this happens.[13]

3. Extended clinical interviewing

To these exploratory interview studies of individual physics students, this paper adds the method of ''extended clinical interviewing,'' as developed by Eleanor Duckworth.[14] Duckworth's extension of Piaget's technique for eliciting children's spontaneous thoughts[11] acknowledges that, in clinical interviewing, the researching of students' developing understandings also extends those understandings. By ''having [*learners*] take their own understanding seriously, pursue their own questions, and struggle through their own conflicts,''[15] this interviewing method involves students in using their process of questioning as a way to learn.

As they respond to a researcher's questions, learners clarify for themselves what they understand and what confuses or intrigues them. Thus the interview's engagement of learners and researcher, together with the subject matter of their study, combines both researching of how understanding of that subject matter develops and teaching of it.

The researcher who is simultaneously a teacher, working with one or more students across multiple sessions, creates a setting safe for expressing tentative ideas. Such safety is crucial; inside of a learner's seeming incoherence is some beginning of interest, reasoning, and thought which can grow and change, but if not respected, may shut off. The interview itself unfolds through learners' intrigue with the subject matter and their responses, explorations, and efforts to make sense of it. The researcher brings learners into contact with the subject matter by providing complex materials that are not prestructured to demonstrate a single effect, property, or path to analysis. Such materials are thoughtfully chosen for their potential to evidence the phenomena under study through multiple entry-ways, along angles and routes that manifest its complexity differently, thus stretching and deepening learners' observations and reflections. The researcher's interactions are grounded in this same commitment and sensitivity to learners' ways of developing understandings of the subject matter. These interactions include periods of silent observing, questioning of what learners notice, do, and think, questioning that tests the researcher's emerging ideas about learners' understanding, and the addition of more materials.[16]

Duckworth's method encourages the researcher to analyze interviews interactively during sessions and reflectively afterward. Rather than reducing a session to models or simplified accounts, the reflective analysis retains details and novelties of students' work and conveys them through narratives.[17] The narratives make evident passages, connections, and confusions that are inseparable from how learners come to understand. They also show how these understandings engage with, and are formed from, deep consistencies within the phenomena. For example, students notice and investigate consistencies in how sun exposure affects autumn trees' change of color,[18] how a poem's strange wording can sensibly cohere,[19] and how it is that some things float in water and others sink.[20]

In contrast to the standardized interviewing used to identify and posit similarities among students' responses, which are then categorized as ''misconceptions,'' this method does not attempt to compare, abstract, or posit such similarities. By treating learners' thoughts as inextricable from particulars, it analyzes details of development that will not be noted by interviewing that judges learners' responses against desired outcomes. Additionally, this work departs from assumptions about teaching and learning that underlie ''misconceptions'' studies. These include assertions that students must recognize failures or shortcomings in their own ideas and, instead, accept what are considered ''correct'' explanations or ''answers'' and that standardized testing can measure deficiencies in students' understanding and inform further instructional actions.[21]

Other clinical studies also attend to particulars in what students say, yet unlike this method, those particulars may be used in developing aspects of empirical theory, which is distinct from interviewing narratives.[22] Additional to other clinical practices is this method's view that teaching and research are inseparable. This is expressed through concerns for materials that open the subject matter to many forms of investigation and interactions that uncover new phenomena, confusions, or ideas that take learners' questioning further.

4. Interviewing Joann

I engaged Joann's interest in exploring magnets during five extended clinical interviews. We met for an hour or more in an unoccupied undergraduate lab at her university. We began each session by sorting materials I provided (and augmented each time in response to her work). Sometimes an effect Joann noticed while sorting, for example, a compass needle's deflection when she moved a magnet—or a new material—once, a magnetite rock—elicited her interest in investigating.

I supported her investigations through observing and finding needed tools (such as scissors and tape). I shared her interest and surprise upon finding something new and asked questions to extend her work, and my understanding of it. Sometimes I pointed out an effect or tool that deepened what she noticed and explored. However, I did not direct her thought or activities toward any specific outcome.

Soon after each session, I transcribed its audiotape and wrote a report detailing Joann's experiments and discussion. These reports, and discussions of them with readers, assisted my preparations for subsequent interviews, my understanding of Joann's investigation, and of ways for supporting it.

This writing sometimes showed me differences between Joann's thoughts and my inferences made while interviewing. While interviewing, I sometimes inferred that her understandings about something (for example, of which magnet ends attract) were settled. Upon later reflection, I recognized places where her use of an understanding remained tentative.

Joann participated as a volunteer. She did not record her work in writing. This limited her developing understanding of magnets. Her recollections from prior sessions were incomplete. When encountering some phenomena in a modified context, she often worked out her prior understandings anew.

Below, after briefly describing the first three interviews, I narrate the fourth one in more detail.

B. Studies of Faraday

Physical behaviors originating in Faraday's researches, and understandings of their laws, have inextricably passed into tools and technology of everyday life and into our more elaborated field theories. While these results are commonly applied, Faraday's process of learning—evolving through specific experimental details—is mostly not familiar to students and teachers of physics.

Faraday's *Diary*[23] provides a resource, unique in the history of science,[24] for exploring his process. Spanning four decades, its sequential entries describe materials, experimental efforts, observations, speculations, and wonder. Portrayals of Faraday drawing upon it and other documents convey perspectives of: biography,[25] cognitive psychology,[26] religious influence,[27] and historical origins of field theory.[28]

The historian Gooding used *Diary* entries, along with one experiment's replication, in analyzing Faraday's thinking about experiments. Gooding inferred that Faraday often considered multiple ideas at once, without testing a single hypothesis, or deciding between specified competing ones. Many possible paths remained available to Faraday; sometimes he resumed a previously abandoned path. In Gooding's view, most historical, philosophical, and textbook accounts of science, attending only to verbal (published) data, portray experimentation as if determined by researchers' expectations. By contrast, he argues that experimental learning involves what the experimenter does and thinks.[29]

Below, I trace Faraday's learning about the behaviors of samples suspended between the poles of the electromagnet he designed.[30] I observe how what he did informed what he understood and tried further, as recorded in *Diary* entries.[31]

II. JOANN

Responding to my announcement during her college algebra class, Joann volunteered. Eleven years earlier, she had graduated from a city high school. During this study, she was a second year major in social psychology at a public university, planning to teach elementary school. She described herself as an organizer of things and thoughts, ‘‘so I can know what is there and ... improve it.’’ [32]

Joann's refrigerator door was crowded with magnets. She recalled her wonder at her mother's use of sewing scissors, rubbed against a magnet, to pick up stray pins. She had never used a magnetic compass, or thought about what it might show. While untrained in science, she found magnets, materials, and learning intriguing.

A. Preceding experimentation with magnets and needles

1. Opposites attract, October 11

Joann's surprise upon noticing that when she moved a bar magnet, the needle of a nearby magnetic compass also moved, opened into the investigatory activities of our first session. The compass needle's red end turned to follow that magnet. But something made the needle's white end tip up; that was the same magnet's other end.

Joann put the black bar magnet on the table. Picking up a second black bar magnet by an end, Joann poked its other end toward the first magnet. The first magnet was pushed away; with repeated poking, Joann made it scoot across the table. When she tried this again, the two magnet ends came together. Then Joann realized she had flipped the end of the magnet she was holding. I asked Joann for her thoughts about the ‘‘pushing away’’ we saw. She called the ‘‘pushing away’’ ends ‘‘negative;’’ those pulling together were ‘‘positive.’’

I said I did not understand what she meant by ‘‘negatives’’ and ‘‘positives.’’ Pointing to the two magnets' pair of attracting and symmetric-appearing ends, she told me again that those ends were ‘‘positive.’’ I was still confused. Joann now elaborated her idea through a symbolic analogy. She supposed that, like multiplication, magnet ends with the same label (positive ‘‘times’’ positive, or negative ‘‘times’’ negative) would come together (a positive result), but magnet ends with opposite labels (positive ‘‘times’’ negative) would push apart (a negative result).

Excited by her idea as it developed through her articulation, Joann exclaimed:

> J That makes sense (*laughing*) ... I wonder if it's true!

I asked if we could find out more about this. Joann was unsure about starting; how could she tell apart the black bar magnets' two ends? Again, she probed the compass with a magnet. She now decided to call ‘‘negative’’ the magnet end that drew the compass needle's red end. I found a tiny piece of tape; since it looked like a ‘‘minus’’ sign, Joann put it on one magnet's ‘‘negative’’ end. She found the end of the other black bar magnet, which came together with this labeled ‘‘negative’’ end. Calling that end ‘‘negative,’’ she also labeled it with tape.

Now Joann tested her idea. She brought the second labeled end toward the compass. She expected that it would draw the compass needle's red end, just as she had seen happen with the first magnet's labeled end. When she tried this, the compass needle turned its white tip toward the second labeled end. This finding, not what she expected, pleased her:

> J ... So that blew that whole theory ... So it is the opposite of what we said ... Opposites attract ... Learn something new every day! (Oct. 11, 1994)

The multiplication analogy did not work, but had enabled her to propose a test whose result she could readily interpret. Although she exclaims here that her ‘‘theory’’ is overturned, the thinking it expressed was resilient in her thinking during our subsequent interviews. On each occasion, she remade this understanding of opposites and sames through further checks of that analogy.

2. Compass-magnet, October 25

The next week, spontaneously noticing that magnets did not pull on some materials, Joann commenced a systematic sorting of metals and other available samples. She suspected magnets are only naturally occurring, their behavior not under human control. Otherwise ‘‘magnets’’ would be designed for special purposes; for instance, picking up plastics. Perhaps this understanding contributed to her doubt, later, that the act of rubbing a needle against a magnet could make it into a magnet.

Attention to asymmetry, in what magnets and metals do, elicited her notice of something more about the compass. She said its needle could not be ‘‘metal.’’ A magnet end attracts either end of metals, but only one needle end.

Joann guessed the compass needle was a magnet; I asked if she could show this. Centering our longest bar magnet (5 in. long) on a ‘‘nondistinguishing’’ cork, she made it pivot on the cork by circling it with a horseshoe magnet. She interpreted this motion as an analogy for the compass needle's turning toward little magnets she had moved past it. By working through this analogy between two experiments, Joann came to a novel extension of her understanding of the compass:

> J ... So isn't it, the magnet always points north? So north is the magnetic pole?[33] That's weird ... I think that compasses are made with a magnetic arrow. The arrow itself, the pointer is the magnet. (Oct. 25, 1994)

Joann's observing and detailed questioning of materials made this use of experiment as analogy possible—and its inference about properties not directly visible to her.

3. Magnet-like needles, November 1

The next week, Joann noticed a pin, that had simply touched a magnet, pulled on another pin. She devised a systematic way to test her ideas about the means by which this property transfers from magnet to metal wire. She used an unmagnetized steel wire to probe steel wire strips that had ‘‘touched,’’ ‘‘rubbed,’’ or been placed ‘‘near’’ a magnet. It was her idea to also add a fourth (control) wire, which was ‘‘never near’’ a magnet. Although nothing responded to her probe wire, Joann noticed faint attraction between the ‘‘touched’’ wire and the ‘‘rubbed’’ wires.

In investigating this further, Joann rubbed pin tips randomly across the surface of a horseshoe magnet, and probed the tips together. Most times, those tips did nothing, or slightly attracted. Once, the tips pushed away. We exclaimed over this. Although Joann wanted to make this happen again, she could not. After another rubbing, the pin tips attracted.

I asked Joann about what she was doing when rubbing. She then refined her method, by rubbing pin tips against either the same, or the opposite, magnet sides. This changed what we saw and enhanced the magnitude of these effects. She could then work out consistency in what pin tips did. Tips rubbed against the same horseshoe leg pushed apart; tips rubbed against opposite legs came together. Joann laughingly suspected rubbed pin tips behaved like magnet ends, without recalling the rule.

Joann had been working only with pin tips; I asked about the pins' unrubbed ends (their heads). In switching from pins to headless nails to needles, Joann repeated her experiments of probing rubbed tips. Although this seemed repetitious of what she'd already done, this work clarified and extended her understanding of rubbed tips. I asked again about the needles' other end, the eye. Joann rubbed two needle tips against the same magnet side. The tips pushed away, but the tip of one pulled on the other's eye.

> J When one [*needle end*] is repelling, the other will connect ... It automatically works as an opposite ... Freaky.

While strange and surprising, Joann found this consistent with her other inferences about magnet ends.

When I asked about compasses, Joann probed one with a rubbed needle's tip and eye. The compass needle's response was the same as that between two rubbed needles. Joann refrained from interpreting this as evidence that compass and rubbed needles were magnets. Her other experimental tests seemed discrepant with this analogy, compelling her caution. That analogy remained incomplete; Joann was not quick to assert it as something settled (as an ''answer'' judged for its ''correctness'' might be) in a way that might close off further investigation. She did use it to extend her thinking and continue her experimenting.

B. Swinging needles, November 22

During a break in our sessions, I prepared for ways Joann's investigating might develop. Some activities not described above suggested her curiosity about measuring and comparing magnets' pulling strengths; although I considered ways of approaching this, Joann never resumed such questioning. I saw another option in her explorations with magnet ends and partial analogies between a compass needle, a magnet, and magnetlike rubbed needles: making a compass from a magnetized needle. But while I was then intent to see her inferences and experiments take this form, she was free to do something else—and did. She never made a compass.

1. Threads

This time, Joann asked me what we were doing. I suggested hanging things from threads. She threaded needles and tied strings around nail heads, pin heads, and a magnet in a plastic sphere. While doing this, she recounted her refusal to listen to her husband's ''logical'' explanations of our magnet activities:

> J ...Nope, I can't learn it any other way but doing it by myself! (Nov. 22, 1994)

Interacting with needles as if sewing, she immediately diverged from my expectation of (compass-like) suspensions about needles' middles.

Joann tested these threaded objects through an experiment of her own design. She placed the horseshoe like an arch, ends down, on the lab bench; previously she had oriented it only horizontally. She held threaded objects above the arch's top and watched what happened. The sphere magnet's plastic case was half blue, half green; when dangled over the arch top, it reoriented: green toward one side, blue toward the other (Fig. 1). Joann felt it wobbling and tugging on her string:

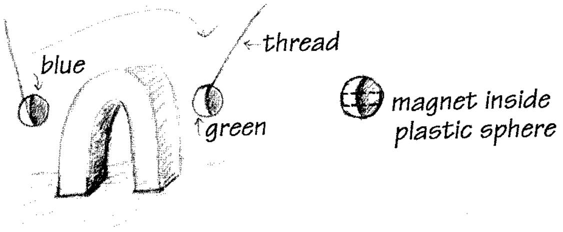

Fig. 1. A blue/green sphere magnet is held by a thread. One colored side turns toward one horseshoe leg, one toward the other.

> J alive almost, a little mouse trying to swim against the current. (Nov. 22, 1994)

Joann stated this reorienting as a pattern from observation: ''green'' turned to the horseshoe's ''undented'' leg. Not casting this as an inference about opposites and sames, she next hung the nail in the same way. It twirled about, over toward one horseshoe side, but did not stop moving in relation to the magnet (Fig. 2). Joann now wondered if its preference for one magnet side was like what she had seen before with needle and magnet ends.

Still, the nail's wiggling puzzled her. She felt the string holding it back, the magnet pulling it on, as two contending pulls:

> J Like the string which is a physical thing and the magnet pull is a physical thing, but it's not something you can touch and grab. The string is something you can see. (Nov. 22, 1994)

The visible string made apparent an invisible but physical pull. Joann grasped the complexity of this equivalence—physical and real—that went beyond visible appearance. From this experience with string and analysis of pulling, she inferred analogically what made the nail wiggle:

> J ...Have you ever ... gotten a string, pull it [*from both ends*], and it kind of wiggles, right in the center? I think that's sort of like what this is doing. There is a pull from the magnet and a pull from the string, and it sort of wiggling. (Nov. 22, 1994)

But, suspecting that the string's knot around the nail influ-

Fig. 2. The nail twirls above the horseshoe's top.

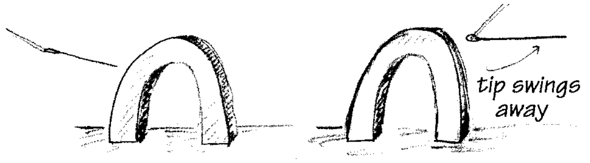

Fig. 3. The needle's tip points toward one horseshoe side. When suspended near the other side, the needle swings up, its tip pointing away from the horseshoe.

enced what was happening, Joann switched to the threaded needle. She held the needle by its threads, tip down, pendulumlike. Its antics were amazing:

> J It looks like it's alive!

With more practiced looking—and feel of the thread's tugging (''Oh wow! It's pushing'')—Joann discerned pattern in the needle's dance—its tip oriented toward one horseshoe side, its eye toward the other. When she tried to hold the tip end near the side attracting the eye, the needle swung around. Although visibly supported only by the thread at its eye, the needle stood nearly horizontal in the air (Fig. 3).

Its tip was pushed away from the magnet.

2. Inverting ends

The needle tip happened to flick against a horseshoe leg. Its behavior immediately changed. The tip now turned toward the leg that had just pushed it away. Delighted, Joann repeated this; a touch changed a needle's repelled end into its attracted end.

Further repetition extended Joann's observations, which enabled her to sort out consistency in what the needle did: ''it works now.'' I said I was confused; she clarified. Previously, she had noticed that rubbed needles either attracted each other or pushed apart. This experiment connected that behavior to the needles' contact with the magnet's end:

> J ...whatever [*magnet side*] I touch with the tip of the pin is what ... the tip of the pin becomes attracted to. It's attracted to whatever [*magnet side*] it touches. (Nov. 22, 1994)

But when I asked, she could not infer whether this meant touch made the needle the same—or the opposite—of the magnet side:

> J ... I don't know if it [*touch*] makes it [*needle*] the opposite [*of magnet side*] or if it makes it the same. I'm not sure. (Nov. 22, 1994)

What she knew was specific to what just happened. This did not, by itself, tell her how opposites and sames worked. Although I assumed she recalled this (from earlier sessions), she did not. She worked it out again later—when it became crucial to interpreting what she then saw.

Joann was then impressed by the ''something'' the needle had, compelling it toward, or away from, the magnet:

> J It doesn't have a mind or an instinct ... but something that forces it ... that has to do with the strength of the magnet. (Nov. 22, 1994)

With this reflection, Joann took her questioning from observation of needles' ways of orienting, to the underlying dynamics. She came to such questions about force only through this session's careful attention to needles, the magnet, and the pattern of relation between them. But Joann did not—in this or our last session—identify or puzzle over this force's spatial character, even though her suspended needles made apparent some evidence of the magnetic field.

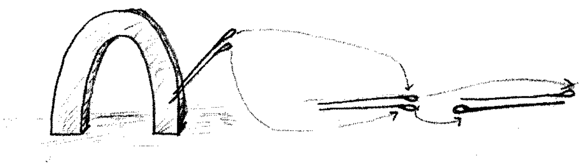

Fig. 4. Two needle tips are touched to the same horseshoe side, and laid with tips matching. They immediately swing around; one needle's eye now matches the other's tip.

Not sure what to try next, Joann paused. I suggested that retrying the previous session's experimenting with repelling pin tips might clarify more about what we had just done. It did.

3. Pairs of needles

Joann probed a pin with a magnetized needle: nothing happened. Puzzled, she exclaimed that she did not understand this.

The pin rolled on the table, over near the magnet, but was not attracted. That simple event had meaning for her—given by her own prior experimenting with metals:

> J Oh, no wonder! A pin that doesn't [*attract to magnets*] at all! Now which metals did we determine work [*with magnets*]?

I listed all metals tried without indicating outcomes; Joann added my silver bracelet. She did not identify which metals were attracted, or classify the anomalous pin. Instead, dropping that inquiry, she pulled out two ''fresh'' needles, and used them, unthreaded.

Joann touched both needle tips against the horseshoe's same side—as she had done the previous session—but then varied her test. When she laid them, tip matched to tip, on the lab bench, the needles immediately spun around. Each eye matched the other's tip (Fig. 4). This was startling:

> J Did you see that?
> E Yeah!
> J ... That's neat! ... That was real. Try it again. (Nov. 22, 1994)

The same thing happened again, but this clarified nothing—''I wonder why?''

Joann now deepened the systematicity of her method. She prepared two needles again, trying at each step to treat them the same. After touching each tip to the same horseshoe side, she checked its attraction for that side. Laying one needle on the table, she probed its tip with the other. Tips pushed apart.

Joann did not understand this, although she had seen it in the previous session. Identically prepared tips acted like what she called ''opposites:''

> J It's like the left side of the magnet gave different qualities to two magnets [*needles*]. Wonder what would happen if I did a third. (Nov. 22, 1994)

Touching a third needle tip to the same horseshoe side, Joann probed each pair of tips in sequence (Fig. 5):

> J ... All the tips push away. Hm. Shouldn't some of them attract? (Nov. 22, 1994)

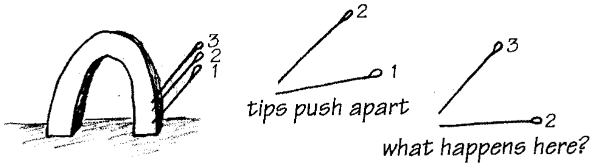

Fig. 5. Three needle tips are touched against the same magnet end. The first pair of needle tips repulse each other. The third tip might attract them. It did not.

Without referring to her prior work, Joann expressed her puzzlement that tips would not come together with tips. She labeled each needle, and systematically tested it again. Through this repetition and articulation, she realized another possibility for the needle's consistency:

> J ... There's only two possible. Unless it. Unless it means that the left side of the magnet turns the pin [*tip touching that magnet side*] into what the right side of the magnet has. Do you know what I'm saying? ... say the left side ... is positive and when I put a pin tip on the positive side, it automatically turns that tip negative. (Nov. 22, 1994)

This understanding is new, although the experiment seems similar to the previous sessions' observations of repelling between needle tips rubbed against the same leg and attracting between eye and tip. Here she has come to that same consistency again, by a different route. She has deepened her understanding of it further by carefully working out the relationship of inversion between a given magnet end and any needle tip rubbed against it. But she has not yet integrated into this understanding the pulling or pushing which happens when opposites and sames combine.

4. Opposites attract

Now knowing that her needle tips were all the same (''negative''), Joann tried to proceed further—did that make them repel? She said she could not remember how magnet ''positives'' and ''negatives'' worked, except that ''we finally refuted'' her first idea about it. I asked what she remembered. Pulling out a prior session's transcript I had just given her, she quickly read the reasoning she had developed about magnet ends.

She now made sense of the needles' preparation, what those needles did, her first (multiplication) analogy, and her later analysis:

> J ... by putting all the tips on the positive [*magnet*] side ... each one of these [*tips*] is negative, so therefore because they are all negative, they won't attract, because they are all the same. So that's why they are not doing what I thought ... I thought that the same things would attract ... . (Nov. 22, 1994)

Although at our first session and in this one, Joann called her initial (multiplication) analogy ''refuted,'' in fact (as the statement ''I thought that the same things would attract'' reveals) it was not replaced or removed from her understanding. It remained integral within her thinking, a resilient part of the way through which she worked out connections to the idea ''opposites attract'' and to what three needles did. Through it, combined with her subsequent experience and thoughts, she found the same natural invariance anew, and now extended it beyond the initial context of two magnets probing a compass needle.

By doing the same test with other needles and nails, Joann became able to say more. A needle, that touched a magnet end, had positive and negative ends like the magnet. However, the needle end had the quality opposite that of the magnet end it touched. This order—strange seeming, yet now made wholly consistent—intrigued Joann; she wanted to work out more about magnets:

> J ... I want to know it like from not knowing anything! (Nov. 22, 1994)

This remark revealed her delight in, and awareness of, the developing of her own understandings that happened through her thoughtful experimenting with materials, and without dependence on authoritative instructions or explanations.

Joann closed this session with further tests to establish whether needles could transfer ''magnetic qualities'' in the same ways that magnets could. These tests were inconclusive. There was still space for doubt in her evidence. She would not go beyond evidence to conclude that rubbed needles really were magnets.

C. Joann's exploring

From a grain of wonder and interest at a compass needle's disturbance by a bar magnet, Joann's work with materials continued to elicit her investigatory and thoughtful responses. She came upon more to notice and try with those materials and invented ways to systematically check what she thought was happening. While her awareness of effects and connections among them became evident through her work and responses to my participation, her awareness of how this learning developed was limited, as she kept no written record. Yet many instances—such as when, upon observing suspended needles' dance, she returned to probing needle tips touched against magnet ends and found both strangeness and sense in what they did—convey her widening understanding of consistencies among what magnetlike things do.

III. FARADAY

In 1845, the surroundings of Michael Faraday's life were displaced from the bookbinder's apprenticeship, through which he had passionately tried experiments he read about in books. He had already served two decades as Director of the Royal Institution. His extensive researches, including the discoveries of magnetic rotation (1821), electromagnetic induction (1831), and his reanalysis of electrostatic induction (1837), secured the prominence of his work and ideas within science internationally. Yet the intensive pace of his early laboratory work was now often interrupted by episodes of poor health.[25]

A. Preceding experimentation with light and glass

Acting on an inquiry from Thomson[34] in September 1845, Faraday reopened his old search for evidence of connections among electricity, magnetism, and light. He began by applying static and current electricity directly to transparent samples and solutions and looked for changes in the state of polarization of polarized light sent through these samples. Analysis with a Nicholl's eyepiece revealed no change in polarization. But a mid-September variation changed this: Upon activating a cylindrical electromagnet, Faraday observed perceptible rotation in the plane of polarization of light transiting a sample of his own formula of leaded ‘‘heavy glass.’’ [35] This effect occurred only when the light’s path was oriented in certain ways with respect to the electromagnet. Faraday associated this response with the agency of a ‘‘*new quality or force*’’ (7550)[36] whose orientation character he regarded as made visible in the curved line patterns assumed by iron filings when scattered near magnets.[37]

Wondering if electromagnetism elicited other ironlike magnetic behaviors, he tested ‘‘heavy glass’’ in several ways detailed in his handbook for students.[38] But the glass did not move toward an ordinary magnet, iron filings did not stick to it, and a sample floated in water did not move when the electromagnet was turned on.[39] Realizing how observation of the subtle optical effect depended on the electromagnet’s substantial increase over ordinary magnetism, Faraday sought to accentuate it by specifying the making of a more powerful electromagnet. The new electromagnet’s current-bearing coils were wound on a half cable chain link.[30] With it, the previously observed optical effect was enhanced and a new mechanical effect became evident.

On November 4, Faraday first used the new electromagnet to probe glass for magnetic behavior by another standard test. He hung a bar of ‘‘heavy glass’’ ($\sim$ 150 g—Ref. 40) by a length of cocoon silk tied around its middle, so that it balanced horizontally and was positioned midway between the electromagnet poles. A glass enclosure protected the suspension from air currents. The glass bar’s long dimension was obliquely aligned with the axis between the poles. Upon activation of the electromagnet by ten Grove’s plates[41] serially connected, the bar oriented in a way Faraday had never seen:[42]

> 7902. ... not so as to point between *N*[*orth pole*] and *S*[*outh*] but across them ... when the current was stopped the glass returned to its first position.

Glass’ turning, crosswise—‘‘equatorial’’—to the ‘‘axial’’ alignment between poles, disrupted a commonly held assumption that all materials responded to magnetism in ways analogous to that of iron. Instead, Faraday saw this as another example of ‘‘the new Magnetic property of matter’’ (7907) already shown, in some transparent materials, through his polarized light experiments. He then sought—and this time found—evidence that magnetism affects materials of all types, and that its action is mediated by curved lines which extend out from magnets into the surrounding space and materials.

During the following days, Faraday suspended various sorts of samples: transparent and not; metal bars, powders held in a paper sling, and solutions contained in glass vials. Without fixing sample dimensions or volume—and with some doubts about sample purity and identity—he recorded whether samples oriented like glass or like iron when the electromagnet was on. He did not measure the strength of different samples’ responses to the electromagnet,[43] but qualitatively noted these variations with adjectives: ‘‘exceedingly well’’ (7940), ‘‘feebly’’ (7951), ‘‘not so strong’’ (7943). All were affected: some oriented axially like iron (paramagnetic), some equatorially like ‘‘heavy glass’’ (diamagnetic), while copper and some metals exhibited a curious ‘‘revulsion.’’

Faraday was intrigued by copper’s behavior: steady off-axial alignment during battery connection; upon disconnection, execution of oscillatory spins toward, and away from, axial alignment. This was nonanalogous to iron, which, under the thread’s torsion, reverted from the true axial alignment to its initial position without post-connection vibrations. For a day (November 7), Faraday tested copper, altering the timing and order of battery connection, diagramming copper’s swings and reflecting on his confusions over this effect. By the next day (November 8), he had begun making connections between this puzzling evidence and ‘‘my old principles’’ regarding induced currents. Battery connection and disconnection changed the curved magnetic lines in the gap, inducing temporary currents—with their associated magnetic properties—in the copper bar.[44]

With copper’s anomaly now seen as consistency, Faraday proceeded to test still more materials: acids, bread, shellac, salts, bone, and more metals. When copper did not perform as well, he suspected the battery and renewed it. Under both old and renewed battery, one metal’s orienting was startling:

> 8027. *Bismuth.* Not Magnetic. *But* is like heavy glass ...Is better than any other thing for shewing the glass position, i.e., the equatorial position. (Nov. 8)

Bismuth’s turning was a wonder. The diamagnetic response, first evident in dielectric insulators, was most pronounced in a metal.

Asking many questions, Faraday considered whether bismuth’s other properties (crystallinity, poor conductivity, thermoelectric behavior) were connected to this additional anomaly.

B. November 10, 1845

1. Questions

The following Monday, Faraday’s *Diary* entries resumed with reflective questions. Might solutions of iron salts, which demonstrated weak magnetism by orienting (or ‘‘pointing’’) axially, also exhibit the optical effect? Although only a few transparent materials exhibited the optical effect, this mechanical effect was different:

> 8081. So all things *point* ... .

Expanding an idea first articulated on November 4, he supposed that samples point either equatorially or axially depending on how the effect’s ‘‘degree of quality’’ differed between them and their surroundings. He speculated about successively immersing glass, water, and air, in each other. Extending his thinking to varied contexts—that might lead to new analogies and understandings—he wondered imaginatively how pointing influenced earth, air, and tree leaves (8082). He also asked what would happen if an oriented sample was nudged aside: would it resume ‘‘pointing,’’ or not?

2. More samples

But Faraday postponed action on these questions, proceeding instead with further samples, some recently borrowed. Remarks on samples, their circumstances, and orienting were sometimes followed by alterations in what he did or thought. A clean scrap of lab porcelain oriented magnetically (axially); this surprised Faraday—other glass didn’t. He then cleaned it in acid, but its behavior was unchanged (8089). Freshly cut beef and apple turned equatorially, unlike the old dried beef tried one previous day. China ink’s indifference to electromagnetism was more confounding: Could two conflicting effects be ‘‘neutralizing’’ each other (8094–6)? Ex-

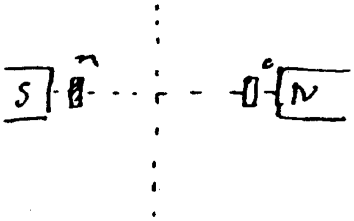

Fig. 6. Faraday's own drawing, a top view of the electromagnet poles (*N* and *S*). Two positions of the bismuth bar are represented by boxes. Drawing 8115 in the *Diary* (Ref. 23).

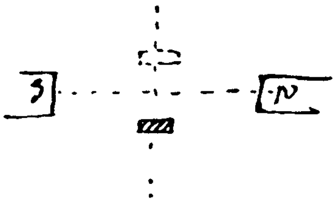

Fig. 7. Faraday's drawing, showing two positions for the bismuth bar, on either side of the electromagnet gap. Drawing 8109 in the *Diary* (Ref. 23).

tending a prior finding that broken chunks, hung in a sling, oriented like the whole piece (7931), Faraday ground bismuth into powder. It still oriented ''exceedingly well,'' but that response was diminished in finely pulverized spar (8097-9).

Faraday next switched from comparing specific samples to looking at the behavior itself. Led from his last reflective question, he nudged suspended samples of copper, ''heavy glass,'' bismuth, cadmium (8101–8107). All but copper resumed equatorial pointing.

3. New standard

No magnetic test distinguished bismuth from ''heavy glass''—except that bismuth's pointing was more pronounced (8083,8100-5). He now adopted bismuth as standard diamagnetic:

> 8106. *Take Bismuth henceforth* as the substance representing this class of bodies ... .

This marked a new development in Faraday's experimental strategy.

For several weeks he ceased testing long lists of materials for their magnetic response. Having found a material-dependent behavior, he selected the material exemplifying it most. Then, with material kept constant—the same bismuth rod[45]—he investigated the spatial aspects of the complex force law. This investigation was not mentioned among the reflective questions opening that day's entries.

4. Motions in space

Upon initiating this change in what he was questioning, Faraday immediately changed the apparatus. A 6-in.-long thread replaced the short silk suspension. Its adjustable ceiling attachment allowed repositioning of the bismuth rod anywhere in the electromagnet gap (8108). All previous samples were hung at one spot—the gap midpoint. Faraday now watched for bismuth's response at each different position when the magnet was turned on (Fig. 6). He spoke of examining something new:

> 8108. ... the Magnetic field by the bar of bismuth ... .

In this use, ''field'' refers to the physical space around the electromagnet's poles, and not yet the understanding we now hold.[46]

Faraday commenced detailed exploration of a space made dynamic by bismuth's response to invisible lines curving from the electromagnet poles. This new evidence shows lines doing more than making iron filings form patterns or inducing current under their transience. Those familiar cases alone do not provide sufficient analogy for interpreting bismuth's motions; to extend beyond analogy with them takes new experimenting. Through that experimenting, Faraday extended his evidence and understanding of those invisible lines and their effects on materials; they were physical and not merely symbolic.

What happened in this space was not immediately analogous to the ''pointing'' of samples suspended at the gap's midpoint. Faraday hung bismuth, its long dimension vertical, midway between the poles but off-axis, just outside the gap (Fig. 7). With the electromagnet on, it swung out along the equatorial line, away from the gap's midpoint. It stayed there. Upon battery disconnection, it swung back. It did the same when suspended at the symmetrical position on the opposite side of the gap. When two bismuth rods were suspended, one at each of these symmetric positions, they both moved outward when the electromagnet came on:

> 8111. ... the magnetic force *seemed* to make them repel each other—but this was only the simultaneous occurrence of the two first actions.

Faraday expressed doubt that the rods' behavior could be accounted for by analogy with other repulsive behaviors (for example, acting along a straight line between two like magnet ends). The appearance of that analogy was superficial here; something else was happening.

Other small details eroded the use of repulsion as an analogy. An unpaired rod also moved out. The equatorial ''pointing'' of bars suspended at the gap midpoint was symmetric with respect to bar ends. But magnetic repulsion, by contrast, acts between pairs of ''similar'' poles; polar samples have ''opposite'' ends which exhibit different, nonsymmetric, behavior.[47]

Faraday continued with other combinations and positions. He substituted ''heavy glass'' for bismuth, and hung ''heavy glass'' at one gap edge, bismuth at the other. The results did not change, except that ''heavy glass'' did not do ''nearly so well'' (8112). Although Faraday earlier asserted that only asymmetric samples would manifest the new magnetism (7906), he now found that shape did not matter. Suspended bismuth cubes, spheres, and bars all moved away from the gap midpoint (8113).

5. Peculiar force

Within the gap, he hung the vertical rod near either electromagnet pole, on axis (Fig. 6). Upon battery connection, it swung toward gap midpoint and stayed

> 8116. ... *permanently held out,* being apparently repelled from the pole.

Upon disconnection, it swung back. If suspended at midpoint, the bar stayed transfixed. From this, Faraday interpreted the midpoint as a balance between forces, a ''place of

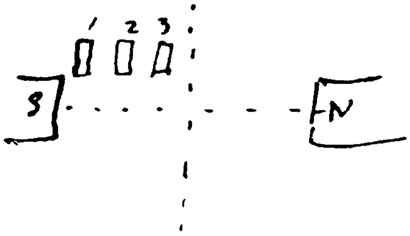

Fig. 8. Faraday's drawing showing three different off-axis positions, 1, 2, 3, for the bismuth bar. Drawing 8118 from *Diary* (Ref. 23).

rest'' (8117). He remained uncertain about whether these magnet-applied forces were repulsive.

Faraday successively hung bismuth at several off-axis positions just outside the gap (Fig. 8). Upon battery connection, from each position, the bar swung, first obliquely, then directly out from the gap. The curved paths of these motions replicated neither the curves of magnetic lines that extend out from electromagnet poles (invisible, but made evident in iron filings patterns), nor imagined curves that would be everywhere crosswise (isonormal) to them.

Through close attention to spatial position, magnetic lines, and bismuth's motion, Faraday came to a novel geometric interpretation of the magnetic force's directing agency. This was not a result of the curved shapes of magnetic lines, but of differences in their strength.[48]

> 8119. Its[*bismuth's*] endeavor is in fact not to go along or across the curves exclusively—but to get out of the curves going from stronger to weaker points of magnetic action.

Faraday's explorations of bismuth's confusing motions made evident something patterned, invisible, and nonanalogous to other forces: a ''new and peculiar action'' (8121–8124). Again he questioned whether analogies with repulsive forces applied. This force,

> 8128. ... the only case, I think, of repulsion without polarity. ...

acts along curves whose shapes vary from point to point, not along ''right lines'' between polar opposites.[47]

The analogy with repulsion redirected Faraday's thinking and experimenting. Resuming the horizontal suspension of elongated samples in the gap midpoint, he now immersed them in a glass of distilled water. He watched how bismuth, ''heavy glass,'' and copper bars turned when the magnet came on. Each pointed just as in air, but ''heavy glass'' went ''more weakly and slowly.'' This extended other inferences connecting behavior to sample volume and relative magnetic response. Being so large, the glass had to displace more water; with a magnetic response closer to water, than to air, the relational difference was much less (8131–8135). The next day, Faraday held this inference in doubt, unsure whether the motions were dependent on surroundings or ''absolute'' (8143). He suggested tests with other liquids, but then waited another week to try.

In these experiments, Faraday was acting on ideas expressed in that day's opening reflective questions, that pointing motions evidence a relational quality, differing between sample and surroundings. The spatial work with bismuth raised this question again for him. Perhaps he regarded this relational quality—the force's magnitude in materials—as possibly contributing to the force's directionality. By testing it here he seems again to be sorting materials for diamagnetic or magnetic response, dropping exploration of the force's directing action. But he grouped both effects together; both tell of positionally dependent strength or deficiency. The next day Faraday observed:

> 8144. ... Bismuth goes *from strong to weak* ... may be because it is deficient in the ... action, and so is displaced by matter having stronger powers, giving way to the latter.

Faraday's understanding grew by retaining awareness of the phenomena's complexity—and not splitting apart factors (associated with the force's magnitude and direction) that he had begun identifying.

IV. WAYS OF LEARNING FROM PHENOMENA

Learning happened for Joann and Faraday through their interactive work with details: of phenomena, of their experimenting, of their thoughtful questioning. Something small—two pin tips pushing gently apart, glass turning in air on a silk thread—caught their notice; its significance for them was shaped by their prior experience and thought. Intrigued to find out more, they engaged it further. The understandings they develop through interplay between activity and thought are at the same time uniquely theirs, and coherent with what magnetism does.

A. Exploration and doubt

These experimental narratives do not depend on an external logic to pass from statement to statement or on method to move from predictive hypothesis to definitive outcome. They are unlike conventional texts that expect students to learn from demonstrations of logic and method. Instead, Joann and Faraday tease out workings of physical consistencies from details of what happens in their improvised tests.

These explorations often open with, and are sustained by, playful interest and curiosity. By actions—Joann in dangling a threaded nail near a horseshoe; Faraday in suspending copper so it spun—they expressed playful interest. In these ways, they gathered evidence sufficient to allow identifying aspects of phenomena or experimental practice that could be clarified by more systematic study.

The systematicity of their work deepened with their awareness of what the phenomena did, and with what their own questions were. For example, Joann initially rubbed pins randomly across the horseshoe. Upon noticing pin tips repelling once, she developed more systematic methods of rubbing and distinguished effects of rubbing against each magnet end. Faraday's work also deepened in systematicity, from his initial testing of all kinds, shapes, and sizes of materials to the selection of one—a bismuth bar—for detailed study.

Their exploration proceeds, not by progressively refining explanations, but by exposing previously unnoticed ambiguities in the phenomena, and uncertainties in interpretation. This exposing deepens the space of their confusions, connecting it to further possibilities in the phenomena and thoughts about that. From these confusions and possibilities, doubt may develop, becoming a more articulate means for probing the understandings forming through the investigation.

This deepening of exploration through confusion is evident in Joann's narratives. Joann's attention to asymmetries, between what metals and magnets do, exposed the possibilities of experimentally comparing the bar magnet with the compass, and later of comparing rubbed needles with each other and with magnets. By coming upon end-dependent repelling and attracting among pairs of different items (magnets, compass needles, rubbed needles), Joann revisited her confusions about how ‘‘positive’’ and ‘‘negative’’ worked. Her work through these confusions extended her observations and ways of thinking connected to understanding ‘‘opposites attract.’’ But she was also increasingly aware that what magnets do is more complex than this ‘‘opposites attract’’ property. Her confusion, about demonstrating what this further complexity could be, restrained her from equating rubbed needles with magnets.

During his first experimenting with diamagnetism, Faraday’s awareness of ambiguities and uncertainties connected to doubts he already held and used for extending his thinking. For example, nine years before, he had probed chilled metals with a magnetic needle.[49] Although it responded only to iron and nickel, he remained open to doubt, and the possibility that all metals are magnetic. Among early reflections upon discovering heavy glass’ equatorial orienting, he noted this effect challenged ‘‘those who say’’ everything aligns like iron (7908). He used this doubt, that materials respond uniformly to magnetism, in continuing to search out different orientings (equatorial, axial, copper’s ‘‘revulsion’’) while varying sample composition. By contrast, in a few brief sessions, Joann did not develop her confusions into articulate doubts about what she observed and understood.

In these explorations, explanation and confusion or doubt function inversely to their roles under conventional instruction. There, students’ acquisition of correct explanations are rewarded, while students’ expressions of confusion are seldom acknowledged. Students and teachers regard confusion as a detriment to academic success defined by production of ‘‘answers,’’ and not as an opportunity for exploring and learning. In the work narrated here, if explanations are treated as ‘‘answers’’ accounting for the phenomena, part of the investigation’s potential may be lost or omitted. But doubt, catching on complexities in the phenomena and thought about phenomena, does not hold any explanation secure. By working through their confusions and sometimes developing them into doubts, these investigators extend what they wonder about and question.

B. Coming to know and ‘‘misconceptions’’

Joann and Faraday deepened the sense they made of phenomena by adding to their experience and responding to details in that experience by adapting their interpretations. These ways of working cannot be condensed into summaries and models of how one goes about learning magnetism. Joann’s work with a threaded needle evolved from amazement at its dance to discernment of pattern, notice of inversions in this upon touch against the magnet, rubbing experiments with needles in pairs and threes, and inferences about needle ends. Faraday’s work with bismuth evolved from surprise at its crosswise orienting to further tests of this, construction of a ceiling suspension, and study of its dynamical response to position in the field. While what they did enriched what they observed and understood, this did not evolve as a sequence of prerequisite events or conflicts through which they had to pass in coming to know.

Similarly, the understandings of phenomena Joann and Faraday developed cannot be summed up by ‘‘answers’’ or explanations composed final to their investigating. The whole of what they tried is integral (although not always explicitly expressed) in their understanding. For example, the sense of consistency and complexity that emerged through Joann’s work with three needles prepared alike, is not expressed by the summary result that all three tips repulsed. The knowledge formed was complex, like the phenomena and the ways of investigating.

Thus the ways and evidences of their learning do not conform to ‘‘misconceptions’’ depictions which reduce novices’ understanding of something to an incorrect belief which is regarded as resistant to, but in need of, change or replacement by the correct one.[50] These two learners’ initial and developing understandings did not function like discrete entities inhibiting acceptance of more adequate explanations. The development of their thinking did not hinge upon exposure to, or conflict with, externally provided correct explanations.

Instead, the investigators’ initial thoughts (which some analysis might transcribe into ‘‘misconceptions’’) made possible the interconnected questioning and experimenting that took these understandings further. When Joann exclaimed ‘‘I want to know it like from not knowing anything!’’ she spoke out of an experience of using her own deepened noticings of what she did not know as beginnings for the observations and inferences through which she came to know and want to know.[51] Through their resilient engagement with what they did not know, what Joann came to know about opposites and sames, and what Faraday came to know about induced currents and bismuth’s motion, became more connected with the complex and subtle consistencies of magnetism and materials.

C. Analogy

In something seeming new, these investigators often look for analogies to other phenomena, experiments, or even unrelated processes. Although the investigations proceed detail by detail, thinking through the analogies goes beyond those details, to work out consistencies that apply broadly. Analogy-widening thought, along with experimenting widening what is observed, make new learning from nature possible.

Joann’s analogies arose as an implicit part of her unfolding observations and efforts to express them. The analogies’ limitations and possibilities became more apparent as she explored them further in experimenting and in responding to my questions. For example, from noticing compass needles’ orienting, Joann inferred that a compass needle and a magnet might be alike. It was by responding to my question (how could she show that) that she developed her initial inference into an analogy that was itself another experiment. The cork-pivoted bar magnet only crudely mimicked the compass needle’s delicate response to a bigger magnet. However, Joann’s work with this larger scale analogy opened her thoughts to another analogy at further increase of scale: between how compass needles respond to magnets and to Earth.

Faraday also used experimental tests to check out his ideas of possible analogies among disparate-seeming effects. By contrast with Joann, whose work evolved implicitly toward her use and analysis of analogies, Faraday sought out analogies and probed their limitations and possibilities as an explicit part of his researching. For example, observations of the electromagnet’s influence upon light transiting heavy glass elicited Faraday’s interest in what other ways magnetism might become evident in materials. Taking iron’s magnetic behavior as an analogy for the new behavior under study, he applied standard tests to check heavy glass for iron-like magnetism. One novel variation (the suspension of glass between electromagnet poles) showed glass' crosswise orienting. This behavior, nonanalogous to iron, became apparent through investigation of a possible analogy with iron.

The analogies Joann and Faraday used to extend their understandings were developments of their own prior experience with materials (Joann's wriggling string, Faraday's study of varied materials informing his selection of bismuth as standard) and with thought (Joann's multiplication, Faraday's analysis of curved paths in induction). While analogies formed through thought might not draw upon relationships inherent in the phenomena, their use facilitates the forming of more adequate analysis. Faraday initially supposed all suspended metals would behave like iron, all nonconductors like ''heavy glass.'' By unsettling this apparent analogy, copper's ''revulsion'' took Faraday's thinking further, both in understanding a new example of electromagnetic induction, and in interpreting other complex responses of conducting samples.

Joann's inexperience with physical analogies was a constraint. However when she continued her thinking through biological analogies (''a little mouse,'' an ''alive'' needle), she was aware of their inadequacy and could still come to a new inference about the suspended needles:

> J ...It's got something. I know it doesn't have any living qualities, but something that forces it...that has to do with the strength of the magnet. (Nov. 22, 1994)

Faraday was explicitly aware that seemingly incongruous analogies could take his analysis further in productive ways. He wrote of actively searching for inventive analogies in a letter dating from his first experimenting with diamagnetism:

> You can hardly imagine how I am struggling to exert my *poetical ideas* just now for the discovery of analogies and remote figures respecting the earth, sun, and all sorts of things—for I think that is the true way (corrected by judgement) to work out a discovery.[52] (Nov. 13, 1845)

D. Invisible consistencies of nature

This paper's narrative from Faraday's work briefly excerpts from his long investigation of evidences that make apparent the invisible field characteristics of magnetic force. Our picture of fields persisting in space even without sources or media, carrying physical properties, as agents of force (elaborated in the quantum view) has evolved beyond those early explorations. Yet coherent understandings formed through his integrating of diverse evidence and thought. Integral throughout this work was Faraday's conviction that natural phenomena behave consistently; this persisted even when such consistency was masked.

Although Joann's recognition of natural consistency initially drew upon superficial features, this recognition was still present as an expectation. For example, she expected things visually alike to behave alike. Her awareness of consistency, how it may underlie diversely appearing phenomena, and how she might probe consistency in her experimenting, deepened during the sessions. For example, when a pin rolling near a magnet was not attracted, she first thought that strange, but then inferred the pin was made of a different metal from the other pins. Yet in this incident, her conviction was too tentative for her to experimentally question what sort of metal that might be (even when I mentioned her previous study of metals).

1. Unity

Faraday's private investigating was motivated by a belief that natural forces somehow were connected.[28] To him, the September discovery (the rotation of polarized light upon transit through materials near electromagnets) evidenced such unity—between light, magnetism, and electricity. After examining that belief by ''strict and searching'' inquiry, he made it public in reporting that discovery:

> 2146. I have long held an opinion, almost amounting to conviction ... that the various ... forces ... have one common origin; or ... are convertible.[47]

To him, his November discoveries, illustrating the same unity, showed it inherent in all materials. In later work, he continued seeking to extend this unity, for example, between gravity and electricity. Negative results did not erode his conviction:

> 2717. ... They do not shake my strong feeling ... though they give no proof.[47]

This certainty—of something there in nature—while going beyond evidence, is not a certainty opposing doubt. It is not a certainty about specific facts or representations (which is perhaps the kind of certainty that is cultivated in students under ordinary instruction with its emphasis on answers). It is more a certainty that questioning comes somewhere to understanding, that nature works consistently.

It is this sort of certainty which could develop through every student's encounters with the physical world and with thinking about those encounters. Joann's work illustrates how a sense of this certainty can develop in complexity. For example, she initially probed the tips of pins rubbed randomly across the horseshoe magnet. When she observed that this same preparation produced two effects (attracting and repelling), she looked for and worked out a rubbing method through which she could produce the same effect consistently. Still, her sense of consistency was not broad enough for her to suspect that pinheads exhibited a corresponding consistency. In response to my questioning she tried this observation. The resulting behavior seemed ''freaky,'' yet it also ''made sense'' in showing a deeper consistency among all the magnetlike things, one she had not guessed was there.

2. Analysis in space

We use fields in analyzing phenomena abstractly in space: To each point in space, a field mapping assigns the scalar or vector quantities displayed by the field at that point. This mapping, from space to values or vectors, is continuous, as are the point to point changes in the values or vectors being mapped. Such field mapping is not an obvious way of rendering observational data.

Faraday's investigation of the spatial character of bismuth's response to electromagnetism was a development from his prior researches, including measurement of electrostatic charge at various positions around charged conductors and observation of association between induced currents and changes in ''magnetic lines.'' Through these studies, Faraday came to see part of the phenomena's complexity in space and in connectedness through space and media, and to doubt then-conventional representations of force as an action ''at a distance.'' But Faraday found that even attention to orienting and spatial position (the features identified in map-making) would not adequately convey the invisible consistency governing bismuth's dynamic motions. His analysis went beyond map-like representations and, integrating evidences taken from different samples and surroundings, he inferred a new kind of consistency that bound together space, material, and motion.

However, Joann never did draw upon her many observations to develop a way of explicitly noticing and stating spatial dependence. Some of her tests (such as checking whether holding a wire ''near'' a magnet made it ''magnetic'') indicate opening awareness to properties of position. In our final session (Nov. 29), she investigated how pins stick to any magnet's ends, but not its middle. When I encouraged her use of a suspended needle, she noted change in its orienting at a bar magnet's geometric middle (not where a paint mark divided it: ''the paint is wrong''). But she spoke of such effects as being localized properties of magnets themselves and did not infer that magnets changed anything in the space around them.

Wonderful, ordered, and strange, magnetism eludes convenient encapsulation; sorting out and uniting what happens in space, in motion, in materials, is subtle work not fully reducible to any single procedure or map. By contrast, most texts assert field models of magnetism only symbolically, without exploring observable behaviors or graphic mappings. Students' engagement with the puzzling complexities of phenomena (some of which Joann noticed) that field analysis addresses will be absent from such instruction. Perhaps students' understandings of field phenomena can be extended through inquiry that combines students' direct experimentation (such as Joann's and Faraday's efforts) with students' investigation of field analysis (which neither had access to). Both experimenting and analysis could combine in exploratory learning that allows all the episodes of doubts, analogies, and questions, which make each student's way differently intriguing.

E. Learning and experimenting

These narratives from Joann's and Faraday's learnings from phenomena, while distinctive in method and time, can deepen our understanding of what learning and teaching physics can involve. In settings where learners are supported in expressing and exploring *their* ideas, their understanding of the strangeness and consistencies of physical phenomena can develop through experimenting. The complexity of real phenomena admits beginnings of curiosity and questioning accessible to any learner and opens to a multitude of ways of researching.

This is unlike the models, simplified explanations, simulations, and logical arguments that, through much reuse in instruction, become worn into a single track not leaving space or time for students or teachers to extend their understandings of this very wide physical world. Since the physical world is so immediate, opportunities for connecting student interest to it cannot be far from any classroom of any level: a pair of magnets, straws, cups and water, a long rope. What can be different is our willingness to listen, and to trust the phenomena and students' resourceful investigating of phenomena.

In Joann's and Faraday's narratives, what is involved in ''learning to learn'' is evident through details of what they did. Joann's observation deepened: Initially noticing only a compass needle's turning, she later observed only one needle end ever turned toward a certain magnet end. Similarly, Faraday, at first noting only whether or not suspended samples oriented ''as heavy glass,'' began identifying qualitative differences among such responses. Initially surprised by what a pin rubbed against a magnet would do, Joann eventually began searching out variations and connections among what pins, needles, and magnets did. My interactions also contributed; in trying to clarify something for me, she often extended her work into a further experimental test or thought. Their learning also developed through refinement and variation in experimental practice (Joann's systematic rubbing, Faraday's long thread) and study of prior work they found relevant (Joann's reading of her transcript, Faraday's careful *Diary* recording and study).

Their learning is also a practice of analysis, which is not kept distant from their observing and experimenting. Joann invented analogies in interpreting what happened; sometimes she analyzed an analogy experimentally (the multiplication idea), widening what she knew. Faraday, by contrast, could draw upon more experience in composing analogies, and a practice of deliberately seeking out and developing analogies. Joann also analyzed many observations and reflected on their connections (for example, collecting common responses of magnets, compass needles, rubbed needles, when wondering if needles could be magnets). Faraday's analysis, by use and critique of spatial patterns, developed the law of bismuth's motions in space. Throughout experimenting and analysis, their learning extended awareness of consistencies in physical phenomena; that deepened conviction in consistency was a resource for continued questioning, sometimes giving it form.

All of this work of ''learning to learn'' does not happen in discrete steps that can be identified and executed separately, apart from the investigation.

By contrast, such ''learning to learn'' is marginal in much physics instruction. Emphasis on results, exam performance, and correct explanation leaves teachers and students with little space for noticing learning. Ways of coming to understandings that diverge from text presentations are seldom encouraged; ignored or regarded as common ''misconceptions,'' they may never develop beyond their apparently nonsensical beginnings. Teaching by experimentation is risky; exploratory activity can disrupt how a course structures materials and explanations and how teachers and students usually relate. Pausing to respect individual students' development through questioning is time consuming; its outcomes unpredictable. Learning through experimenting takes open acknowledgment both of what is known and of what is not known; when made without fear (by either students or teachers) of being ''wrong,'' that clarity assists in forming questions. Such questioning threatens the usual authority ascribed to teacher and text; by engaging in it, both teachers and students risk changing how they associate, work, and make new understandings.

The uncertainties and vulnerabilities that make space for questioning are not easily arranged, either through teaching, researching, or everyday experience. Learning and teaching is usually limited to a familiar restrictive domain typically manipulated through authority, that does not engage students and teachers in a practice of researching and learning together in community. But there can be space for genuine research even among what seems most familiar and recurrent about physics instruction—that pins orient near bar magnets, or that students are often confused. Ordinary experience seldom accommodates probing how things happen in the physical world, or reflection upon how we think about them. However, through it, students can come to notice something that, attracting their interest and wonder, sustains their further observation and investigation.

This paper's examples suggest that such exploratory questioning can extend learning productively both for novices like Joann and even for a researcher with the experience of Faraday. It includes qualities integrating thought and work with materials that are additional to what physics instruction usually elicits, yet are essential for forming understandings through researching phenomena. Thus there is a function at all levels, for curricula that is structured to engage students with their own understandings of phenomena of the physical world.[53]

Currently, most settings for teaching physics, where few faculty and resources of time and materials are available for instructing large numbers of students, do not seem to allow for interactions among student, teacher, and materials such as those that made Joann's investigating possible. But exploring how teaching can become experimental could also involve experimenting with structures of courses and ways resources are provided and used for teaching; this experimenting combines participation among teachers, students, and their schools. Through it, all students and teachers could be supported in finding their own ways to understandings—held in doubt, inferred through analogy and analysis—of what is common and certain in nature.

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[8] A. diSessa, ‘‘Phenomenology and the Evolution of Intuition,’’ in *Mental Models*, edited by D. Gentner and A. Stevens (Erlbaum, Hillsdale, NJ, 1983), pp. 15–33; ‘‘Toward an epistemology of physics,’’ Cogn. Instruct. **10**, 105–225 (1993).

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[10] H. S. Lin, ‘‘Problem solving in introductory physics: demons and difficulties,’’ Sc. D. thesis, MIT, Cambridge, MA, Physics Department, 1979.

[11] J. Piaget, *The Child's Conception of the World*, translated by J. and A. Tomlinson (Littlefield Adams, Savage, MD, 1976/1929).

[12] Clement, 1978, in Ref. 4 and J. J. Clement, ‘‘Observed Methods for Generating Analogies in Scientific Problem Solving,’’ Cogn. Sci. **12**, 562–586 (1988); J. J. Clement, ‘‘Nonformal Reasoning in Experts and in Science Students: The Use of Analogies, Extreme Cases, and Physical Intuition,’’ in *Informal Reasoning and Education*, edited by J. Voss, D. Perkins, and J. Segel (Erlbaum, Hillsdale, NJ, 1991), pp. 345–362.

[13] L. Viennot, ‘‘Analyzing students' reasoning: Tendencies in interpretation,’’ Am. J. Phys. **53**(5), 432–436 (1985); A. diSessa, 1993, in Ref. 8; J. P. Smith III, A. A. diSessa, and J. Roschelle, ‘‘Misconceptions Reconceived: A Constructivist Analysis of Knowledge in Transition,’’ J. Learning Sci. **3**, 115–163 (1993); using classroom excerpts: D. Hammer, ‘‘Misconceptions or *P*-Prims: How may Alternative Perspectives of Cognitive Structure Influence Instructional Perceptions and Intentions?’’ *ibid*. **5**, 97–127 (1996); D. Hammer, ‘‘More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research,’’ Am. J. Phys. **64**(10), 1316–1325 (1996).

[14] Extended clinical interviewing is described, with examples of its practice, in E. Duckworth, ‘‘Teaching as Research’’ (1986) and ‘‘Twenty-four, Forty-two, and I Love You: Keeping It Complex’’ (1991), in *The Having of Wonderful Ideas & Other Essays on Teaching & Learning* (Teacher's College Press, New York, 1987/1996).

[15] E. Duckworth, 1991, in Ref. 14, pp. 135–136.

[16] For further examples and discussion of extended clinical interviewing as a combined practice of teaching and research see the essays in E. Duckworth, 1987/1996 in Ref. 14 and E. Duckworth, *Inventing Density* (North Dakota Study Group on Evaluation, Grand Falls, ND, 1986); E. Duckworth, ‘‘Some Depths and Perplexities of Elementary Arithmetic,’’ J. Math. Behav. **6**, 43–94 (1987). For discussion of how issues of safety, respect, learners' involvement in subject matter, and encountering subject matter through its multiple possibilities, pertain to teaching and learning, see D. Hawkins, ‘‘I, Thou, It’’ and ‘‘Messing about in Science,’’ in *The Informed Vision* (Agathon, New York, 1974). For historical connections to extended clinical interviewing, see Y. Hsueh ‘‘Jean Piaget, Spontaneous Development and Constructivist Teaching,’’ Dissertation, Harvard University, 1997.

[17] For examples of research and theory as description, see M. Armstrong, *Closely Observed Children* (Chamelon, London, 1980); for reflections on this form of analysis, see B. Engel, ‘‘Interview with Michael Armstrong,’’ Elem. School J. **84**, 350–356 (1984).

[18] C. Julyan, ‘‘Understanding trees: Four case studies,’’ Dissertation, Harvard University, 1988.

[19] A study of students interviewed individually: L. Schneier, ‘‘ ‘Why not Just Say It?’: Three Case Studies of Understanding Poetry,’’ Qualifying Paper, Harvard University, 1990; and with students interviewed collectively: L. Schneier, ‘‘Apprehending Poetry: A Case Study of a Group of Six High School Students,’’ Dissertation, Harvard University, 1995.

[20] E. Duckworth, in Ref. 16.

[21] D. J. Grayson and L. C. McDermott, ‘‘Use of the computer for research on student thinking in physics,’’ Am. J. Phys. **64**(5), 557–565 (1996), and work cited in Ref. 5, among others.

[22] A. A. diSessa, ‘‘Unlearning Aristotelian Physics: A Study of Knowledge-Based Learning,’’ Cogn. Sci. **6**, 37–75 (1982); diSessa, 1993, in Ref. 8.

[23] M. Faraday, *Faraday’s Diary, Being the Various Philosophical Notes of Experimental Investigation*, edited by T. Martin (Bell, London, 1932–1936), Vols. 1–7.

[24] D. Gooding and F. A. J. L. James, ‘‘Introduction: Faraday Rediscovered,’’ in *Faraday Rediscovered: Essays on the Life and Work of Michael Faraday, 1791–1867*, edited by E. Gooding and F. A. J. L. James (Stockton, New York, 1985); R. D. Tweney, ‘‘Faraday’s notebooks: The active organization of creative science,’’ Phys. Ed. **26**, 301–306 (1991). Another study finding similar complexity in Ohm’s notebooks: J. L. McKnight, ‘‘Laboratory Notebooks of G. S. Ohm: A Case Study in Experimental Method,’’ Am. J. Phys. **35**(2), 110–114 (1967).

[25] L. P. Williams, *Michael Faraday: A Biography* (Simon and Schuster, New York, 1971).

[26] R. D. Tweney, ‘‘Faraday’s Discovery of Induction: A Cognitive Approach,’’ Gooding and James in Ref. 24; R. D. Tweney, ‘‘Fields of Enterprise: On Michael Faraday’s Thought,’’ in *Creative People at Work: Twelve Cognitive Case Studies*, edited by D. B. Wallace and H. E. Gruber (Oxford U.P., New York, 1989); M. F. Ippolito and R. D. Tweney, ‘‘The Inception of Insight,’’ in *The Nature of Insight*, edited by R. J. Sternberg and J. E. Davidson (MIT, Cambridge, MA, 1995).

[27] G. N. Cantor, ‘‘Reading the Book of Nature: The Relation between Faraday’s Religion and his Science,’’ in Gooding and James, Ref. 24; G. N. Cantor, *Michael Faraday: Sandemanian and Scientist* (St. Martin’s, New York, 1991).

[28] These studies include: D. Gooding, ‘‘Faraday, Thomson, and the concept of the magnetic field,’’ Br. J. Hist. Sci. **13**, 91–120 (1980); ‘‘Final steps to the field theory: Faraday’s study of magnetic phenomena, 1845–1850,’’ Hist. Stud. Phys. Sci. **11**, 231–275 (1981); N. J. Nersessian, *Faraday to Einstein: Constructing Meaning in Scientific Theories* (Martinus Nijhoff, Dordrecht, 1984); ‘‘Faraday’s Field Concept,’’ in Gooding and James, Ref. 24.

[29] D. Gooding, *Experiment and the Making of Meaning: Human Agency in Scientific Observation and Experiment* (Klumer, Dordrecht, 1990); also ‘‘ ‘In Nature’s School’: Faraday as an Experimentalist,’’ in Gooding and James in Ref. 24.

[30] The large Royal Institution electromagnet, designed by Faraday, made possible his first detection of diagmanetism. Its form was a 46-in.-long horseshoe, made from a half cable-chain link of ‘‘not the very best’’ unannealed iron, donated by a contemporary naval entrepreneur. A total of 522 ft. of 0.17 in.-diam coated copper wire wrapped the two legs in three concentric coils. The pole pieces were 7-in.-long soft iron rods; their 2.5 in. by 1 in. cross sections faced each other across an adjustable air gap of (typically) 6 in. Faraday activated it with 10 Grove’s cells connected in series (Ref. 41). This electromagnet is described in entry 7874 of Ref. 23, Vol. 4; paragraph 2246 of M. Faraday, *Experimental Researches in Electricity* (Dover, New York, 1965), Vol. 3, and depicted in frontispieces of Ref. 23, Vol. 4 and J. Tyndall, *Researches on Diamagnetism and Magne-Crystallic Action, including the Question of Diamagnetic Polarity* (Longmans, Green, London, 1870). From these descriptions, I estimated the magnetic field in this gap could be a substantial fraction of 1 T (More details are provided in the longer study from which this paper is derived: E. Cavicchi, ‘‘Ways of Learning Physics: Magnets, Needles, Fields,’’ Qualifying Paper, Harvard University, December 1995.)

[31] I supplemented my study of *Diary* entries by suspending various samples, including a bismuth ingot, in the 3/4 in. air gap of an Alpha Scientific electromagnet. When activated by 8 A from a laboratory power supply, the field within this gap was 0.73 T, uniform to within about 0.01 T. Samples were hooked to the end of a 2-m-long nylon thread which hung from the lab ceiling within a cardboard enclosure. With this apparatus I observed many effects described among Faraday’s first accounts of diamagnetism: field-induced ‘‘equatorial’’ aligning of bismuth and ‘‘axial’’ aligning of iron sulfate powder when suspended in midgap, a suspended copper ingot’s ‘‘revulsion’’ from the poles upon cessation of the field, field-induced motions of samples suspended just outside the gap (paramagnetic samples moved into the gap; diamagnetic samples moved outward), and the relative orienting of samples suspended in solutions more or less paramagnetic than the samples. The air gap’s small size (3/4 in.) and environmental factors (especially air currents) restricted my observations to small, high-density samples and inhibited notice of some spatial effects Faraday mentioned (Ref. 23, entries 8115–8120). This laboratory apparatus could not be switched on and off quickly; thus I was unable to observe some responses to rapid switching that Faraday mentioned (Ref. 23, entries 7903-5, 7971). For more details, see Cavicchi, 1995, Ref. 30.

[32] Transcript of October 11, 1994; further excerpts from transcripts will be noted by date following the excerpt.

[33] Joann sometimes used ‘‘magnetic pole’’ to indicate the end part of a magnet where it picked up pins. During this session’s work with magnets and a compass, she made a connection for herself between what she called a magnet’s pole and earth’s geographic poles that she had been told ‘‘are supposed to be the magnetic poles’’ (Oct. 25, 1994).

[34] W. Thomson to M. Faraday, August 6, 1845, in L. P. Williams, *The Selected Correspondence of Michael Faraday* (Cambridge U.P., Cambridge, 1971), Vol. 1, pp. 458–460. Thomson was later Lord Kelvin.

[35] Faraday developed this optical glass formula, in which lead oxide is replaced by silicated borate of lead, two decades earlier. Its specific gravity varied from 5.4 to 6.4, as reported in M. Faraday, ‘‘Bakerian Lecture: On the Manufacture of Glass for Optical Purposes,’’ 1829. See also F. A. J. L. James, ‘‘Michael Faraday’s work on optical glass,’’ Phys. Ed. **26**, 296–300 (1991).

[36] Faraday sequentially number-coded all his *Diary* entries; hereafter, references to the *Diary* will be indicated only by entry number. All excerpts are taken from Ref. 23, Vol. 4.

[37] Faraday’s first observation, on September 13, 1845, of field-induced rotation in the plane of polarization of light transiting leaded glass, is reported in Ref. 23, Vol. 4, entry 7504. This work was published in ‘‘On the magnetization of light and the illumination of magnetic lines of force,’’ 1845, reprinted in M. Faraday, Ref. 30, Vol. 3.

[38] M. Faraday, *Chemical Manipulation: being Instructions to Students in Chemistry* (Wiley, New York, 1974/1827), paragraphs 1280–1281.

[39] Entries 7691 (September 26, 1845) and 7743 (October 6, 1845) from Ref. 23, Vol. 4.

[40] The ‘‘heavy glass’’ bar’s dimensions, given in *Diary* entry 7902, are $1\frac{6}{8}$ in. long and 1 in. square; assuming an approximate specific gravity of 5.4 (from Ref. 35) gives a mass of ~ 150 g.

[41] Grove’s cell, consisting of a platinum (negative pole) foil immersed in nitrous acid in which was placed a porous chamber containing an amalgamated zinc foil in sulfuric acid, was first described in W. Grove, ‘‘On a small Voltaic battery of great energy,’’ Philos. Mag. **15**, 287–293 (1839). One contemporary comparison of commonly available batteries found ten pairs of Grove’s cells most effective: W. Sturgeon, ‘‘Experiments on decomposition of H_2O by voltaic pairs,’’ 1840, *Researches Experimental & Theoretical in Electricity, Magnetism, Galvanism* (Crompton, London, 1850). Later texts report the cell’s high voltage (1.9 V), low internal resistance ($0.1\ \Omega$), and long duty period (3–4 hours continuous delivery of 12–15 A): S. P. Thompson, *Elementary Lessons in Electricity and Magnetism* (MacMillan, London, 1930/1895); S. R. Bottone, *Galvanic Batteries: Their Theory, Construction, and Use* (Whittaker, New York, 1902).

[42] Previous observations of diamagnetism, predating Faraday, include those reported in: A. Brugmans, *Magnetismus, seu de Affinitatibus Magneticis* (Lugduni, Batavorum, 1778), p. 130; A. C. Becquerel, ‘‘Sur les Actions magnétiques excitées dans tous les corps par l’influence d’aimans très-énergiques,’’ Ann. Chim. **36**, 337–349 (1827); M. la Baillif, Bibliothèque Universelle **xl**, 87–95 (1829). Further discussion of the history of diamagnetism appears in G. Boato and N. Moro, ‘‘Bancalari’s Role in Faraday’s Discovery of Diamagnetism and the Successive Progress in the Understanding of Magnetic Properties of Matter,’’ Ann. Sci. **51**, 391–412 (1994).

[43] Tyndall, Faraday’s successor as Director of the Royal Institution, studied diamagnetic behaviors of bismuth crystals suspended in a torsion balance, as reported in J. Tyndall, Ref. 30.

[44] In *Diary* entries of November 7 (Ref. 23, 7961–7986), Faraday records experiments and observations regarding a suspended copper bar’s ‘‘revulsive’’ behavior. Only in entries of November 8 (Ref. 23, 7987–7998) does he connect these behaviors to electromagnetic induction. He devotes a substantial portion of the paper published from this work (‘‘On new mag-

netic actions, and on the magnetic condition of all matter,'' 1845, reprinted in M. Faraday, Ref. 30, Vol. 3) to detailed analysis of currents induced in the copper bar.

[45] Faraday describes the rod as 2 in. long with a cross section of 0.2 in. by 0.33 in. (8192); a mass of ~ 21 g.

[46] Gooding (1981 in Ref. 28) observes that Faraday's first use of the word ''field,'' in a couple *Diary* entries (7979, 8014, 8085) preceding this, refers only to the region of experimentation and activity. Although later defining ''magnetic field'' by lines of force, that expression gained more circulation among Thomson and others.

[47] Faraday describes repulsion in ''On some new Electro-Magnetical Motions, and on the Theory of Magnetism,'' 1821, reprinted in M. Faraday, Ref. 30, Vol. **2**, p. 136.

[48] Lines' strength, not defined here or in the paper published from these studies (M. Faraday, 1845, Ref. 44), varies pointwise with position. With lines' strength interpreted as line density, bismuth moves from regions of concentrated magnetic lines toward regions of dispersed lines. It is, for us, the position-dependent value of magnetic field, $B(\mathbf{x})$.

[49] ''On the general Magnetic Relations and Characters of the Metals,'' 1836, reprinted in M. Faraday, Ref. 30, Vols. **1**, **2**, pp. 217–219.

[50] Refer again to the critiques of Smith, diSessa, Roschelle, 1993, in Ref. 13.

[51] For further examples and analysis of the developing of learning through ''not-knowing,'' see E. Duckworth, ''The Virtues of Not-Knowing,'' in Duckworth, 1987/1996, in Ref. 14.

[52] The quote appears in the postscript of a letter dated November 13, 1845 from Faraday to German instructor Schoenbein (1799–1868) in M. Faraday, *The Letters of Faraday and Schoenbein, 1836–1862*, edited by G. W. A. Kahlbaum and F. V. Darvishire (Williams & Norgate, London, 1899).

[53] Other papers connecting students' learning with laboratory investigation include: H. Kruglak, ''Experimental Outcomes of Laboratory Instruction in Elementary College Physics,'' Am. J. Phys. **20**(3), 136–141 (1952); P. Morrison, ''Less May Be More,'' *ibid*. **32**(6), 441–452 (1964); J. C. Menzie, ''The Lost Arts of Experimental Investigation,'' *ibid*. **38**(9), 1121–1127 (1970); M. C. Robinson, ''Undergraduate laboratories in physics: Two philosophies,'' *ibid.* **47**(10), 859–862 (1979).