Faraday and Piaget: Experimenting in Relation with the World

Elizabeth Cavicchi
Dibner Institute for History of Science and Technology, MIT

The natural philosopher Michael Faraday and the psychologist Jean Piaget experimented directly with natural phenomena and children. While Faraday originated evidence for spatial fields mediating force interactions, Piaget studied children's cognitive development. This paper treats their experimental processes in parallel, taking as examples Faraday's 1831 investigations of water patterns produced under vibration and Piaget's interactions with his infants as they sought something he hid. I redid parts of Faraday's vibrating fluid activities and Piaget's hiding games. Like theirs, my experiences showed that incomplete observations and confusions accompanied—and facilitated—

I thank Ryan Tweney for encouraging me to explore common ground in the experimenting of Faraday and Piaget. Together with Ryan, Ronald Anderson and Elke Kurz-Milcke enhanced my study through our ongoing discussions about Faraday. For their thoughtful responses to prior versions I am grateful to: Consuelo Aceves, Constance Barsky, Jamie Bell, Alva Couch, Elke Kurz-Milcke, Alberto Martinez, Philip Morrison, Chris Smeenk, Sam Schewber, Ryan Tweney, David Williams and the reviewers. Myles Jackson discussed the Webers' acoustics with me; conversations with Friedrich Steinle supported my thoughts about Faraday's explorations. Discussions with Frank James at the Royal Institution enhanced my picture of Faraday. A Piaget study group at Harvard Graduate School of Education including Anne Armstrong, Maria Ale Blanco, Eleanor Duckworth, Fiona McDonnell and William Shorr helped me in articulating Piaget's work. Summer Grove and her parents Bob and Melody shared with me her explorative search. I learned from the crispation explorations of students in my course "Exploring Water through Ways of Doing Art and Physics", including: Kristin Buchholz, Stephen Goldsmith, Alexander Phillips, Melissa Price, Kristen Record, John Ryan, Lisa Sankowski. For laboratory support and discussions, I thank Wofgang Rueckner and Joe Peidle at the Harvard Science Center, and James Bales at MIT's Edgerton Center. Eleanor Duckworth, Claryce Evans, Philip Morrison and Wolfgang Rueckner inspired my studies. This project was partly supported by a Postdoctoral Fellowship at the Dibner Institute for the History of Science and Technology at MIT. I offer this work in the memory of Philip Morrison—Faraday's counterpart—and to Eleanor Duckworth—reexpressing Piaget through teaching.

Perspectives on Science 2006, vol. 14, no. 1

experimental developments. While working with things in their hands, these experimenters' minds were also engaged, inferring new, more coherent understandings of the behaviors under study. Transitory ripples disclosed distinct patterns; infants devised more productive search methods. From the ripples, Faraday discerned an oscillatory condition that informed his subsequent speculations about light. From the infant search, Piaget identified experimenting as a child's means of developing self and world, later envisioning its infusion into education. Taken together, these two stories demonstrate that cognitive capacities emerge in the actual process of experimenting. This finding eclipses the historical context in its implications for education today. When learners pursue their own experiments, their minds develop.

1. Introduction

How do we ever get to know the physical world we inhabit, with all its diverse patterns and subtle behaviors? It is oversimplified to say that experiments give us this knowledge. Many experiments are framed by ambitions to extend and consolidate our control over nature, where only a particular outcome matters. If, instead, we look at the *process* of coming to know other things, a relational character emerges within the experimenting. This process goes on when we act with genuine curiosity, watch what happens, and, keeping an open and uncertain mind, respond by trying something else. Not only the physical system is changing; we are changing too, in what we notice, do and think. The mutuality of change and effect—in us and in the world—is relational.

Faraday and Piaget

That relational activity permeates the experimenting of natural philosopher Michael Faraday and psychologist Jean Piaget. Working a century apart, Faraday and Piaget interacted directly with what they were trying to understand. Through these interactions, they made new observations, questions, and ways of interacting. Their experimental actions and their interpretations evolved together, and this was generative for continuing their investigations, and for supporting much later work by others in physics and in psychology. From everyday materials like water in a dish, Faraday evoked such effects as a rippled surface. In investigating these patterns, he developed original ideas which contributed to his emerging picture of a physical field pervading space (Gooding, this issue). Similarly, within another facet of ordinary life—the activities of children—Piaget elicited and probed developing processes that otherwise went unnoticed.

Faraday engaged nature as a partner in a dialogue that was not merely an exchange of material, questions, evidence, but also transformational of both researcher and subject. For example, Faraday mounted coaxial discs having radial slots; as these discs spun at different rates, the coinciding of their slots provided a discontinuous visual stimulus (seen through the slots) having a steady appearance (Faraday's analysis of aquatic rotifers is a similar example, Gooding, this issue). This constructed optical illusion exposed the false steadiness of other periodic motions. In the structure that Faraday introduced both to the act of viewing and to producing the physical effect, Tweney discerns interacting processes of cognition, perception, and physics (Tweney 1992). These relations go on in unscripted and dynamic ways, always undergoing further interaction, restructuring, or other changes, yet without fragmenting or diffusing apart (see Gooding, this issue). In fact, experimenting deepens the coherence we apprehend in the world. Gooding portrays this quality of Faraday's experimenting as "convergence," where the phenomena exhibited in the apparatus iteratively co-stabilize with his understanding of it (Gooding 1990). Convergence does not result in one fixed truth about reality; truth remains relational. We are integral with the world we seek to understand, and change in the course of experimenting.

Piaget's experimental practices offer further perspectives on those of Faraday. Although Piaget sought to research children's thinking, he found he could not do this without engaging children actively with the physical world.[1] A child who is exploring begins "talking about actions he has just performed", saying things that reveal internal thinking (Piaget [1941] 1965, p. vii). Piaget came to this realization through extensive longitudinal studies in the infant years of his own three children. For example, in grasping a toy for the first time, an infant comes into a relation with it that may stretch or change the infant's capacities for acting, and for distinguishing self from others. Subsequently, Piaget deliberately posed provocative activities to children while researching their intellectual development in such varied domains as morality, number, time, space, geometry, and logic (Piaget [1932] 1965, [1941] 1965, [1946] 1970; Piaget and Inhelder [1948] 1964; Inhelder and Piaget [1955] 1958, [1959] 1964). These activities were not just methods for finding something out, they were transformative: children came to differently understand the world by acting on and in it. Piaget perceived thought and action as inseparable, coevolving the "operations" by which we relate to the world. Experimentation lies at the core of his analysis: it expresses the ongoing interaction among thought and action that is essential to all genuine development.

1. Piaget's initial clinical method was a verbal interview in which he sought to elicit a child's "spontaneous conviction . . . when the reply is the result of a previous original reflection"; he did not want to collect replies that simply parroted adults (Piaget [1926] 1964, p. 11). Under this method, observation of children provided informative guidance to start a research study, and to check its eventual inferences.

Exploratory and Relational Experimenting

Faraday and Piaget engaged with complex behaviors for which they could not account by any pre-existing explanation. They respected this complexity by seeking out the full range of its terrain, and by being open to whatever might emerge. What they observed and uncovered had epistemic value; it widened their view of the phenomena and gave rise to new groundings for future questions and experiments.

Characterizing work of this kind as "exploratory experimentation", Steinle contrasts it from "theory-driven" projects that aim for well-defined outcomes, and thus are cut off from serendipitous findings (Steinle 1996). This description of exploratory experimentation is equivalent to Piaget's insight: action (here in the form of experiments) and thought (here termed "concepts") "codevelop, reinforcing or weakening each other in concert" (Ribe and Steinle 2002 p. 46). What the experimenters do, both systematically and playfully, develops along with the inherent complexity of their subject. It is in making multiple exploratory passes through the material while taking up differing views, that they develop means for understanding its complexity overall (Burian 1997).

These exploratory ways of experimenting have "relational depth": the learning going on is not only about things in the world, for it also involves human understandings that can change ourselves. The value of this awareness is exemplified in Crawford's finding that her own emotional experiences, while studying Faraday's experimental work, functioned at the same time as a window into his creative processes (1985). Confused by Faraday's words, she reached a state of trusting his account, yet accepting her ongoing doubts. Through dwelling a while in this mental state, she became able to extend her understanding of Faraday—and to realize that Faraday himself worked in this way. She identified this experience with a quote by poet John Keats:

> . . . Negative Capacity, that is when a man is capable of being in uncertainties, mysteries, doubts, without any irritable reaching after fact and reason." (Keats quoted in Crawford 1985, pp. 218–219)

Unlike ordinary endeavors geared toward specific results, "negative capacity" means sitting immersed in waves of complexity and confusion and letting relations emerge in the wash and ebb.

To experience an insider's outlook, in analogy to Crawford, I repeated some instances of the experiments described by Faraday and Piaget (for a thorough experimental replication, see Tweney, this issue). Being an experimenter enabled me to observe effects analogous to what they saw, and to face questions and confusions that, while personal, pertained to those of the historical investigators. Other replications of Faraday experiments conducted by historians have demonstrated such qualities as his thorough familiarity with materials, persistence with subtle phenomena, and manipulative prowess (Gooding 1985; Cavicchi 1997, 1999; Höttecke 2001; Tweney 2002). While Piaget's work has spawned countless repetitions, these structure experimental controls in testing his findings, rather than elucidate Piaget's original process.[2] Yet the redoing of historical psychology experiments can elicit insights that are not limited to validity checks (see Kurz and Hertwig 2001).

This paper will explore ways that thinking and action are conjoined in the experimenting of Faraday and Piaget. It follows the relational depth of this process, as each experimenter's understandings of something in the world changed. Paired examples from each will open discussions of their experimenting and interconnections. For Faraday, examples are drawn from his work with water vibrations in summer 1831; for Piaget, from experiences with his infants' searches for a toy he had hidden. Faraday's working observations and conjectures are documented in his detailed *Diary* (vol. 1) and expanded in his subsequent paper ([1831b] 1991). Piaget's "observation notes" are available only as excerpts in the publication ([1937] 1964); in addition his analysis provides a further resource on experimentation.

2. Relations of Observing and Trying

It takes many, many observations to make out what is going on in complex phenomena. The myth that scientists have sudden breakthroughs conceals such extensive groundwork (Ippolito and Tweney 1995). Faraday and Piaget recurrently went back for yet another look, while at the same time perturbing the experimental system. What happened on each second look, was never quite the same, due partly to their involvement with it.

Confusing Wavelets of Water

The patterns that vibration brings about on the surfaces of metal and fluids were familiar to Faraday (see Gooding, this issue). In the 1780s, the German instrument-maker Ernst Chladni found amazing patterns were taken up by sand sprinkled on a metal plate (mounted at its center) when a violin bow rubbed against its edge (Jackson 2004). Thomas Young, one of Faraday's predecessors at the Royal Institution, worked out the wavelike

2. Tests disputing Piaget's finding, that infants lack awareness that external objects persist even when obscured, typically presented many infant peers with the same task (Butterfield 1977; Baillargeon and DeVos 1991). By contrast, the results from a longitudinal study of fewer infants were more in line with Piaget's (Gratch and Landers 1971).

features of light in part through practical comparison with water waves. Young's wave table was still around, and Faraday incorporated it into his experiments. While others had coated Chladni-like plates with water and already described the water's sharply defined rippling[3], Faraday felt they had a "false theory" ([1831b] 1991, p. 335). He looked for more to see and to understand in the fine waves made by vibration, which he termed "crispations" (on Faraday's invention of scientific terms, see Anderson, this issue).

Faraday's initial work with Young's table illustrates how each instance of looking again stimulates more variations in experimenting. Faraday immersed the vibrating Chladni plates in the table's pool, both "so as to have no limit to the water over the vibrating plates", and to minimize the complication posed by ripples reflecting off the water's containing edges (*Diary,* 17 June 1831, §8–12 (1932, vol. 1, pp. 336–337))[4]. He then abraded a glass rod against a circular glass plate mounted just beneath the water's surface. "Beautiful crispations" appeared, distributed radially from a central area of rippled water that diminishes to a ring of quiet water at the nodal radius, and then resumes near the disc's edge. Out beyond that edge, waves made "crossing circles", unlike those associated with the vibration.

To make out better what was going on, Faraday rubbed the rod harder, to increase the disc's vibration. It "sometimes" happened that the wavelets' radial symmetry broke into a tiling pattern of squares, rectangles or hexagons. These figures were most intriguing, yet only "sustained with difficulty". Faraday's turning of the rod in his hands was in moment-to-moment relation with the water's disturbance. It took many tries to develop a touch that gave rise to patterns. Ringing the disc too strongly only made for "tumultuous and broken" arrays at the disc's perimeter. The pattern was remarkable when evoked but dissipated immediately. Getting another glimpse required turning the rod, again and again.

The transitory crispations came about through the relation between Faraday, rod, glass and water, appearing in those moments when somehow everything was in tune. Watching for them while rubbing the rod gave feedback on what he tried, perhaps by developing a synergy in ways that cannot be put in words. But it did not enable him to stabilize the phenomena such that a certain action would always produce wavelets. The next entry suggests this instability by the remark "when the crispations

3. Faraday cited Oersted (referenced in Wheatstone), Wheatstone (1823), and Weber (1825) as predecessors in producing and describing crispations.

4. Beginning in August of 1831, Faraday initiated a paragraph numbering system for his *Diary,* which continued sequentially and unbroken until the *Diary* ends. Faraday's entries on the crispations predate that paragraph numbering system; this sequence began with §1 on 17 June 1831, and ended with §147 on 18 July 1831.

appeared"—implying that often, they did not—and the observation "sometimes they were confused" (*Diary,* 17 June 1831, §13 (1932, vol. 1, p. 337)).

For Faraday, 'confusion' was a far more profoundly disturbing experience than simply noting that wavelets were not sufficiently 'in sync' with each other to yield a sharp pattern. Confusion was involved in how his mind grasped what was happening.[5] These "confused" crispations were not something he could just take in by smearing the patterns' borders. Instead, he kept thinking and questioning.

For Faraday, the crispations' nonappearance and instability was frustrating; yet it was this very quality of his experiment that correlated closest with my efforts with water and a dish. Never have I managed more than screeching sounds and ordinary radial waves when scraping a glass rod against a glass dish of water (for another reuse of glass rods, see Tweney, this issue). And, when I have evoked crispations (by striking the rod against the dish's edge), the patterning is gone before I can move from amazement to description. My first record of them in my own diary expressed this excitement: "crispations petri dish! Yes . . . crispations! . . . again!" (24 October 1997, § 49–51) (see Figure 1). I began to notice, as Faraday suggested in some entries, that the ripples' ordering extends out from the point vibrated.

Confusion that comes momentarily into order is provocative. I pursued the elusive pattern by ringing the dish, again and again. What I watched for was too complex to take in fully in any single viewing.

An Infant's Close, Yet Foolable, Watch

This involvement with complex phenomena through repeated, yet varying, trials, emerges in the pairing of actions between an infant's grasping at something intriguing, and Piaget's efforts to understand the infant's activity. Already from the second day of life, Piaget noticed that the newborn's mouth "seems to seek" the mother's breast after losing it. Other early seeking behaviors included trying to get a thumb back in the mouth, and turning eyes toward where father last was, as if to find him there. Piaget tested this last response by showing himself repeatedly at the same crib-side spot, then hiding and spying as the baby looked again that way, expecting "to see me reappear" (Piaget [1937] 1964, p. 9). But, on not seeing dad, the child's gaze stopped.

5. Similarly, Crawford examined a passage in Faraday's 1838 study of lateral, or transverse, forces of electric currents. She was confused by what he wrote. Her confusion served to uncover origins of a creative development in his analysis of this phenomenon (1985 pp. 216–7).

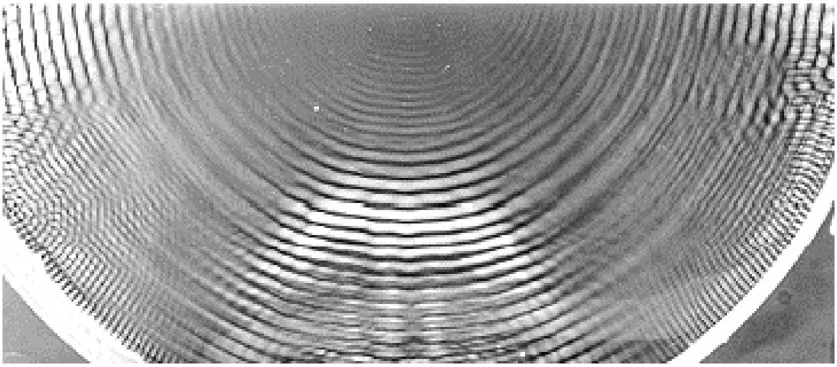

Figure 1. My first print showing crispations appearing as circular rings and superimposed fine lines perpendicular to the glass' rim (or checkerboards) when the petri dish is struck by a glass rod (made on October 24, 1997). The photogram print is made by placing photographic paper under the dish in the dark, and activating an electronic flash to expose the paper to the crispations; this photographic method was developed by Surrealist artist Man Ray and extended by photographer Berenice Abbott (Abbott 1986).

There was no true search. From this, Piaget inferred that the infant took its own action of turning and gazing as synonymous with dad being in that place. The infant did not yet apprehend any distinction between self and other things, and thus lacked a relation with the world.

At nine months, there was more going on between child and things, and this offered Piaget more ways of engaging the child. Attracting daughter Jacqueline with his pocketwatch—prized by each of his children—Piaget gently lowered it onto her quilt. After watching, she reached over and took it. As a variation, he dropped it. She looked with surprise at his empty hand and did not locate the watch. On the next try she first inspected his hand, then found it on the floor. Just once more in eight further drops, did she succeed.

They kept this up for another nine trials. If he lowered the watch slowly down so she could see its entire descent, she found it. When he dropped it, she did not. A few days later, when he dropped something large, she looked on the floor. If it was small she searched his hand. Releasing her toy duck on dad's shoulder, Jacqueline looked only in front of him, not behind (where it fell). In subsequent days, she looked at the ground when something fell, no longer expecting it to be in dad's hand.

Piaget credited Jacqueline's involvement with the object—following it by eye; seeking and handling it in her hands—as her means of working out the path of falling things. Yet her relation with these things was insufficient for sustaining investigation. If the duck dropped out of sight, she did not persist in hunting it. The duck remained bound up with her perceptions and was not yet a separate entity. This limitation on the child's view constrained what Piaget, as the experimenter, could do to productively engage it. Many hiding games failed to hold her interest. This perceptive bond with the object, that kept the child from acting in relation with the world, also denied to the experimenter an adequate means, or 'lever', for elucidating what was going on for the child.

Experimenting by repeated trials with variations is about getting to know the terrain and finding ways of working in relation with it. In Faraday's case, where the phenomena are unstable, rubbing harder on the rod did not bring the crispations into greater clarity. For Piaget, many successive falls of the watch resulted in "negative attempts" where Jacqueline did not retrieve dad's watch (Piaget [1937] 1964, p. 16). Confusion in the effects, and incompleteness in our relation to what is happening, are integral to experimental work. Continuing on, finding yet another variation to try, means staying with the ambiguity that is there without directing it to go away. This patience for deepening understanding is crucial when interacting with a child, who will sense its presence or absence.

3. Explorations with Understanding in Transition

When we ring glasses or play with baby as part of an experiment, those actions—along with their outcomes—attract notice in themselves. Doing something prods us to think about, and evolve, ways of doing it. This process connects with Gooding's idea of "convergence": that continued work with an apparatus deepens our "'sensorimotor' understandings" of what to do with it, together with our cognitive inferences about its behaviors (Gooding 1990, p. 150–151).

For example, Faraday became more adept at crispating diverse fluids on surfaces differing widely in scale: "Can now pass at pleasure from smallest to largest arrangement" (*Diary,* 25 June 1831, §13 (1932, vol. 1, p. 343)). Concurrently, he was intent to make out what was going on in or at the fluid's surface: "The notion of reciprocating waves or elevations gains ground in my mind" (*Diary,* 18 June 1831, §22 (1932, vol. 1, p. 338)). His marginal sketches expressed the surface geometries that he inferred from the crispations' transitory appearances, and combined with his idea that adjacent units in the pattern cycled through opposing motions (Figure 2 Left).[6] Similarly, by way of many, many experiences of reaching for,

6. Recent studies show squares, triangles, lines, hexagons, other regular *n*-gons, and even spirals, appear in the patterns and "quasi-patterns" of "Faraday waves" that are produced both experimentally in vibrated glycerol (Edwards and Fauve 1993, 1994; Besson,

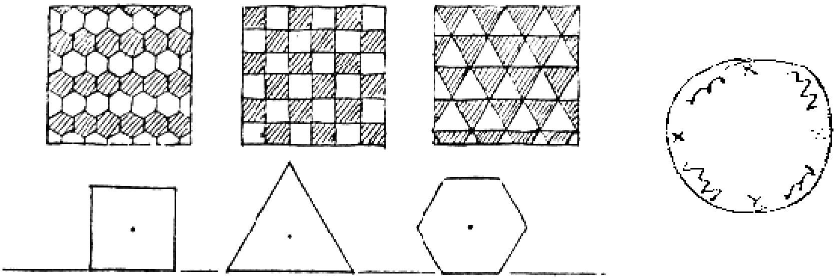

Figure 2. Left: Faraday's sketches of hexagonal, rectangular, and triangular patterns as possible interpretations of the crispations' geometry (*Diary,* June 17, 1831 ¶ 14 (1932, Vol. 1)). Right: Faraday's top-view diagram of crispations' distribution in the water glass; 'x' represents places of still water or weak crispations, while the wavy lines indicate a more agitated surface (*Diary,* July 2, 1831 ¶ 120 (1932, Vol. 1)).

losing, and sometimes finding, toys (and the pocket watch) hidden by their teasing dad, Piaget's infants began to show some awareness of stability in the thing being moved. This development enabled Piaget to test out more elaborate hiding maneuvers, which at the same time extended his own hunches and queries into the child's own sensorimotor relations with its surroundings. Exploring physical things, for Faraday, Piaget, and the baby, was at the same time moving their understandings.

Ringing Sound onto Water

This active role that understanding can take is evident in Faraday's realization of coherence between his lab work and something from everyday life. At one day's end, Faraday recorded that he had seen similar effects before: "The experiment shews at once the cause of the ripple or crispation formed at the surface of water in a drinking glass vibrating under the finger." (*Diary,* 1 July 1831, §118 (1932, vol. 1, p. 353)). The following day, a Saturday, Faraday filled a large drinking glass with water, and ran his finger around its rim to make audible tones. As his sketch shows, the water surface showed regions of quiet water separating disturbances bearing the "confused heaps" typical of crispations (*Diary,* 2 July 1831, §120 (1932, vol. 1, p. 353); Figure 2, Right). By regulating how forcefully he rang the

Edwards and Tuckerman 1996), and theoretically by numerical calculation from model field equations (Müller 1994; Lifshitz and Petrich 1997). The more complex quasi-pattern arrangements (that are not strictly periodic under translation) arose when the fluid container was vibrated by two frequencies at once.

glass with his finger, he could accentuate either the crispations, or ordinary circular waves. Faraday's remark "*Very good*" speaks to this integration among action and physical effect in eliciting more understanding.

Ringing a water glass was analogous to vibrating the glass plates Faraday had first used; this analogy carried new practices with it. The act of running the wet finger around the glass' rim set a whole container—not just a bottom surface—into vibration. The glass resonates audibly; possibly this suggested another instrument of sound: the tuning fork. Faraday next placed a tuning fork to vibrate water directly, without any glass intermediary. He oriented it horizontally. It grazed the water and set up striped ridges, whose crests were perpendicular to the tine's sides. He watched the fork's motion coupled with the water, making "alternate heaps" (*Diary,* 2 July 1831, §123 (1932, vol. 1, p. 354)) unlike the fork's literal displacement (see Gooding's discussion of multiple viewpoints, this issue).

With the tuning fork, Faraday reopened many of his former explorations. For example, on first trying the tuning fork, he rang it loud, soft, and "moderate". Just as these variations had produced differing effects with the glass plates, so it was with the fork. "Loud" put out spurting water jets; "soft" left one tine's ripples too weak to affect those of the other; while a "moderate" ringing showed, in his words "very prettily", a stationary pattern of intersecting waves (*Diary,* 2 July 1831, §122 (1932, vol. 1, p. 353)). The distinctness of the water patterns gave immediate feedback to Faraday's methods for applying the fork. To Faraday, these patterns resembled what happened when plates were vibrated vertically—from spurting jets to feeble humps, and occasionally the crisply-defined waves whose order he sought to describe (for Faraday's response to dynamic patterns and frequencies, see Gooding, this issue). By working out these actions and their effects anew, he could relate the vibrations of a plate, container and fork tine together in his mind.

This mental inference appears clearly in the next session's Diary entry. Faraday returned to materials that he had already tested with the glass plates, but now applied the tuning fork. In liquid mercury, the fork excited ridged waves that dampened under the mercury's high density. He put it ringing into cold oil—the surface leapt into the fountains of over-agitation but showed no wave patterns. Heating the oil changed this: "the peculiar ridges appeared, the oil having now lost that tenacity which it previously had." (*Diary,* 5 July 1831, §129 (1932, vol. 1, p. 354)) Here he created novelty by using a tuning fork as had never been done before, which at the same time connected with his previous observations. This process was cycling and improvisational, not stepwise and linear. That Faraday found it fruitful to initiate fresh explorations with each vibration tool (plate, waterglass, tuning fork) shows how his understanding was in transition: plying the water by different approaches that, combined together, charted movements and patterns in the water.

The interplay among eye, hand and mind, which distinguishes Faraday's crispation work, also emerged among me and my teacher education students one day as we rang wineglasses of water after reading Faraday's *Diary.*[7] We reproduced not only the physical effects, but also the exploratory engagement. Moments after I had started class by running my finger around a glass' rim, the room hummed as the six of us intently rang glasses of various shapes and quality. The first crispations to appear were fleeting and unsustainable (as with Faraday). A teacher, Kristen, found that one particular glass yielded the effect more readily; another teacher, Stephen, assisted by holding its base securely. As two others, John and Alex, evoked crispations, they remarked on how the pattern followed their finger's travel, showing four-fold symmetry (also noted by Faraday; Figure 2 Right):

Alex "They follow you. There are four. There is a set of four."
(Transcript, November 9, 1999)

Stephen saw more: the crenulated waves mimicked Kristen's fingerprint: the water took up her fingerprint! From this observation, an idea for an experiment emerged. If we rubbed the glass with something other than fingers, would the patterns change? I found a wood rasp and hacksaw; we taped their blades to protect the glass. Running each blade crosswise over the wineglass's edge (Figure 3) changed the water surface:

John That's really different.
Kristen Wow!
Everyone Amazing!
Stephen We've really got to something here.
(Transcript, November 9, 1999)

Next, Stephen found a ground glass rod; after repeated efforts to set the water glass in vibration by rubbing with it, he succeeded: the water surface agitated and sprayed a fine mist. To Alex's persistent questioning

7. The class, titled "Exploring Water through Ways of Doing Art and Physics" was an experimental course which I developed and taught at the Harvard Graduate School of Education in 1997 (with Petra Lucht), 1999, and 2000. Each session included lab activities with water and materials, and discussion of readings and experiences in teaching and learning (Cavicchi 2005). I interactively facilitated students' explorations in pursuing their own observations and questions about water. This work expressed the methodology of teaching/learning research developed by Eleanor Duckworth ([1987] 1996, 2001) that adapts Piaget's clinical method ([1926] 1964) for classroom settings.

Figure 3. Left: Two teachers watch while another teacher vibrates a water glass with the teeth of a wood rasp. Right: Two photograms showing crispations produced when a wineglass was vibrated by a string bass bow (November 29, 1999).

about the mist, Stephen supposed that the water churned "at a faster rate". The rasp and saw teeth produced coarse waves, contrasting with the closely spaced ripples made with a finger or ground glass. A lengthy discussion ensued as the teachers tried relating these tools to the water's surface features, and queried what rate and frequency actually mean.

Like Faraday, the teachers found that differing vibration brought out differing effects.[8] Their experimental manipulations developed along with

8. The Faraday scholar and science teacher, Elspeth Crawford, describes a similar experience when she engaged school pupils in making crispation effects in glycerine and other fluids, using a signal generator as the vibrator. Students became fascinated, continuing their projects in after-hours. Crawford, the teacher, learned from the "crackling atmosphere of liveliness and deep satisfaction" that they created (1993, p. 207).

their interpretations, as when Stephen sought out ground glass, got its scraping to agitate water, and analyzed the misting. Their actions in producing waves coalesced interactively with their understandings. When Faraday called the wave alternations "most beautiful" (*Diary,* 28 June 1831, §69 (1932, vol. 1, p. 345)) and the teachers exclaimed "Amazing", their wonder expressed the connection, or 'convergence', they felt in relation with these phenomena.

An Infant Catches on to New Hiding Places

Piaget was exploring the origins of this process in his infants, as they acted on other objects, encountered those things as different from themselves, and handled objects in new ways. An example that expresses transitional qualities in the child's relation to objects occurred when Piaget's son Laurent was at nine and a half months. For months prior, Piaget had played with his son by putting covers over his watch, Laurent's jingle bells, a pencil, or himself. Laurent looked on eagerly, but once the object was out of sight, his interest waned and he did nothing more. In recent weeks, this had changed: when Laurent saw something being hidden, he pulled up the cover. But Piaget, the experimenter, did not let these successes end the game. Next he asked: what does the child make of the watch not being where it was hidden the first time?

> Obs. 44 . . . Laurent is placed . . . between a coverlet A on the right and a wool garment B on the left. I place my watch under A; he gently raises the coverlet, perceives part of the object, uncovers it, and grasps it. The same thing happens a second and a third time but with increasing application. I then place the watch under B; Laurent watches this maneuver attentively, but at the moment the watch has disappeared under garment B, he turns back toward coverlet A and searches for the object under that screen. I again place the watch under B; he searches for it under A. . . . when . . . I again place the watch under garment B, Laurent, whose hand is outstretched, raises the screen at once without turning to A; he finds the watch immediately. I then try a fourth time to put the watch under B, but at the moment when Laurent has both hands in the air; he watches my gesture attentively, then turns and again searches for the watch in A! (Piaget [1937] 1964, p. 53)

Laurent worked out the association between watch and coverlet A through his searches and successful retrievals: A came to be the watch's out-of-sight location. Except for the third trial when Laurent was physically engaged with the hiding, Laurent looked only in the first place. Faraday and my students had vibrated the glass differently and learned by producing more wave patterns; here Piaget varied hiding places and learned how tenuous Laurent's searching still was. In doing this, he treated the difference between how the child looks for the watch, and how an adult might, as meaningful, not haphazard.

Just as Faraday began conceiving a mechanism of reciprocating motions in tuning fork and water, Piaget also worked to interpret what might be underlying the child's behavior. This was not easy since the evidence of a child's actions can be too ambiguous to make out any coherence. For example, when Laurent first became involved in getting a hidden toy by lifting its cover, sometimes he still did not go for it. Piaget wondered "But is this chance or is the behavior intentional?" ([1937] 1964, p. 45). A week later, he wrote it was "difficult to interpret" when Laurent might find it. After that, the child always found an object that was hidden once and Piaget declared "the behavior pattern has now been acquired" (p. 46). Even so, the following days might show lapses.

Confusing as these transitions were, they also demonstrated that change was ongoing. This was essential; Piaget's deepening sense that the child apprehends the world differently from adults could be workable only if there is a process of moving from the child's view to the mature one. He portrayed this process by identifying distinctive transitions which show the child developing his search, such as those excerpted here.

To experience something of Piaget's experimental situation, I experimented with a little friend, 19-month old Summer. We began by exchanging one of her yellow blocks. When I hid it under a napkin, she recovered it immediately, and her sisters and I clapped. Next, I put it under the first napkin, and without pausing, slipped it under a second—a trick Piaget devised after Laurent became able to get the watch hidden under B (following the situation above). Summer raised the first napkin, and then the second—she did not go right for the second napkin (Figure 4); Piaget observed this pattern with daughter Lucienne at 10 months. I adapted the play by crumpling the first napkin around the block, and laying the second napkin on top. Sometimes Summer didn't find it; then, if I tapped the block, or partly uncovered it, she became curious to get it. As she watched, I put the block successively under a napkin, a big cushion, and another napkin. Summer upended the pillow, but did not go on to find the block, even when we tapped it. After awhile, Summer walked off with her block, ending our play.

By trying to respond to Summer with ever more engaging play, I appreciated how much experimenting *is* the interactions. None of these experiments could be planned or staged: just as Faraday continually varied how he hit and placed the tuning fork, Piaget improvised new hiding games as his infants grew. Although I immediately wrote down Summer's

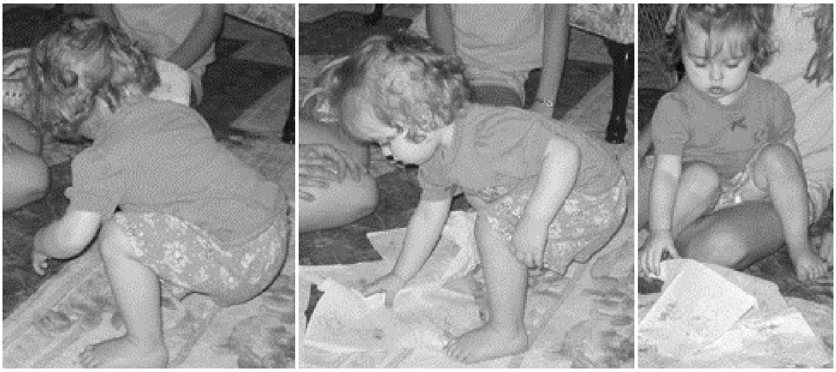

Figure 4. Summer looks for, and finds, her yellow block after I hid it under two paper napkins. Photos by Bob Grove.

searches, much slipped away. My wish for a videotape of Summer was analogous to capturing crispations with photograms.

There was something intrinsically fleeting about the phenomena that intrigued Faraday and Piaget. Observing anything at all depended on interactive methods. Perhaps the historical lack of photo or video documentation motivated Faraday and Piaget to persist in experimenting until their internal pictures stabilized (see Gooding, this issue).

Transitions become Understanding

My experiences with Summer and water vibrations elucidate how improvisation depends on materials. To keep Summer involved, I grabbed whatever was handy; similarly, vibrating water in new ways depended on the availability of tools. Piaget, too, adapted children's toys, crib blankets, his beret, into evolving games with baby. Faraday's well-stocked lab facilitated novel extemporaneous work; however the water-glass was brought from home. Diversity and flexibility in material surroundings enable experimenters to act on their provisional observations and ideas as these occur.

This immediacy is essential; the transitional understandings formed by Faraday, the teachers, and the young children are not static, but in motion along with whatever they are doing and noticing. When something is not just as expected—an overagitated rippling or a multiply hidden toy—the seeker may be provoked in ways that change their relation to these things. Gooding has identified this kind of provocation as holding in common be-

9. As his source for Piaget, Gooding cites Kuhn's analysis of how paradox generates novel thought in a Galilean dialogue and in Piaget's work with children. Galileo developed

tween the experimenting of Faraday and Piaget.[9] For him, the paradoxes that Piaget designed into his experiments facilitate the conditions that are necessary to enable anyone to reinvent what they understand:

> A threshold of ambiguity or confusion must be reached before thought is compelled to experiment in a manner that is open to conceptual reform. Faraday's work often displays this creative use of ambiguity and uncertainty. (Gooding 1990, p. 207)

We see that threshold when Faraday described "confused heaps" in the water-glass, when a teacher interpreted the water as a fingerprint, when Laurent turned back from new hiding place B to the familiar A. There is confusion—yes, yet that confusion is productive. It provides the grounds for reintegrating the perplexing behaviors of experience with deepened understanding (Cavicchi 1997, 2003). A sense of connection and wonder in relation with other things develops as well.

4. Coherence Forming in Relation

As Faraday and Piaget worked directly with water vibrated by glass plates, or a watch hidden from a baby, their experimenting was both shaped by—and building to—a more comprehensive understanding of the physical world and our relation with it. Faraday's persistence in following spatial orientations and relations was not accidental. His thinking was always tending toward what goes on in space (including as a metaphor for knowledge; see Anderson, this issue). Only through experimenting could he work out what this might mean. His field ideas were incipient yet not preformed, continually evolving in response to evidence that he sought out as tests (Gooding 1981). Crawford observed that Faraday gained a fuller synthesis by acknowledging all possible ideas without prefiltering them under theoretical constraints:

> The coherence of ideas was not imposed by any prior framework, but was allowed to emerge from the chaos of thoughts he experienced. (1985, p. 220–221)

Similarly, Piaget deliberately involved babies with disappearing toys, to get at their provisional relation with the world and, more significantly, to follow its changes. Underlying these experiments, Piaget perceived a logic

an argument for an instantaneous interpretation of speed by drawing attention to paradoxes in Aristotelian notions about speed; similarly in Piaget's experiments, toy cars traveling at different speeds and/or distances finished the race in a seemingly paradoxical order. This provoked some children to rethink their criteria for "fast" and "slow" (Kuhn 1964).

of development by which a life "not only becomes an increasingly complex structure itself, but also structures the world around it." (Hsueh 1997, p. 50) For both Faraday and Piaget, the coherence emerging from their experimental work went wider and deeper than the instances of each study. It integrated across the *longevity* of their lifelong commitments to search and re-search action and space in physical phenomena (Gooding, this issue), and in the apprehension of young minds.

The Spreading of Oscillatory Conditions

In working out the displacements of water making up the crispations, Faraday kept his mind open to two contrasting interpretations (for Faraday's caution against letting language influence his interpretations, see Anderson, this issue).[10] The patterns could be composed of stationary heaps that do not change in time, or the heaps could be continually cycling from peak to valley in place like standing waves (for similar experimental efforts to work out whether gold leaf was continuous, see Tweney, this issue).[11] Faraday's previous study of sand swirling on vibrating Chladni plates, disposed him to regard the water crispations similarly, as permanently raised cones kept intact by the water's cohesion (Faraday [1831a] 1991, § 37, p. 328; [1831b] 1991 § 95, p. 345). Under a contrasting position, held by the Webers[12], the water heaps rise and fall. When Faraday shone candlelight across water crispations, its reflection off each heap "traveled, forming endless figures" and he asked "Does not this shew that the waves are reciprocating, i.e. continually moving to and fro one into another?" (*Diary,* 20 June 1831, §25 (1932, vol. 1, p. 339)). Approaching this question through the opposing interpretation, he punched numerous nipples in a metal sheet, then vibrated it in candlelight (see Gooding's discussion of pattern and process, this issue).[13] This model of permanent heaps displayed its inadequacy when light reflected from the sheet ap-

10. Elspeth Crawford investigated Faraday's continued openness to both particle and field interpretations of matter, which resulted in seminal contributions to each (1985).

11. Faraday's uncertainty about the heaps' form makes sense to me; I could not make out the changing contours in time of the crispations in my experiments.

12. Adopting the term "l'oscillation fixe" of Siméon-Denis Poisson, E. and W. Weber described the crispations as composed of parts in vertical motion from above to below the water level, bounded by motionless nodal lines (Weber 1825, p. 411)

13. Wheatstone also constructed a model of the surface and came to a similar interpretation of the water's vibratory motions (1823). He coated the surface with resin, vibrated it, and observed a network of cracks forming in the resin. The cracks suggested that parts of the surface moved up and down while other parts did not. Faraday, too, considered making resin ripples: "Must make permanent elevation of resin . . . see how they appear under the vibrating state of the plate." (*Diary,* 20 June 1831, §26 (1932, vol. 1, p. 338)).

peared as a linear unit, unlike the "traveling" spots of light made by real crispations (*Diary,* 23 June 1831, §45 (1932, vol. 1, p. 342)).

Faraday's understanding distinctly evolved: where initially he supposed crispations were permanent elevations, his work by candlelight demonstrated that their heaps continually rise and fall in place. He began to see the entire fluid as a pendulum-like body in oscillation, influenced by the vibrating force, gravity, water cohesion, friction ([1831b] 1991 §105, p. 349). Any localized displacement of fluid and container rapidly conveys to adjoining parts, extending the patterned disturbance—as one body set in oscillation, not as a pulse progressing outward. This analysis enhanced his further experimenting.

Faraday understood this analysis as differing from the view that crispation patterns are made when traveling waves, coming from opposing directions, intersect. Again (as with the punched metal sheet) he checked this idea by testing its contrary: he cushioned the container's sides with sawdust to absorb reflecting waves. If the pattern was due to waves reflecting off the container's rectangular sides, then with sawdust edges and an irregular shaped container, there should be no pattern. Yet crispations were still produced. Recently two French researchers used this same test to sort out boundary effects; on putting glycerol in an irregularly shaped container and vibrating it vertically, they observed symmetrical patterns of "Faraday waves" (Edwards and Fauve 1993, 1994). In both cases, the experiment derived from, and clarified, the investigator's thinking.

Faraday went further with his experimental tests of the idea that crispations are not composed from ordinary waves that progress outward from a source. With the water glass and tuning fork, crispations appeared even when the vibrator was not a bottom surface. Perhaps the crispations did not depend on any special orientation between water surface and the vibrator. Faraday checked this out by anchoring a wood lath at one end and positioning its other end to dip into the water either normal, or parallel, to the surface. On vibrating the lath with the glass rod, waves of the ordinary kind (with crests parallel to its blade) were "hardly sensible". Instead, there appeared regular ridges "like the teeth of a very coarse comb", whose crests aligned parallel to the lath's direction of vibration (*Diary,* 1 July 1831, §118 (1932, vol. 1, p. 352)). When the lath was set up to immerse a cork into water, these ridges radiated starlike from the cork (Figure 5). Ridges formed when the tuning fork was oriented at every angle to the surface.

Observing that these features appeared on surfaces of incompressible fluids, Faraday suspected that with compressible fluids, like air, the patterns would manifest as alternating densities in the fluid's volume. To test

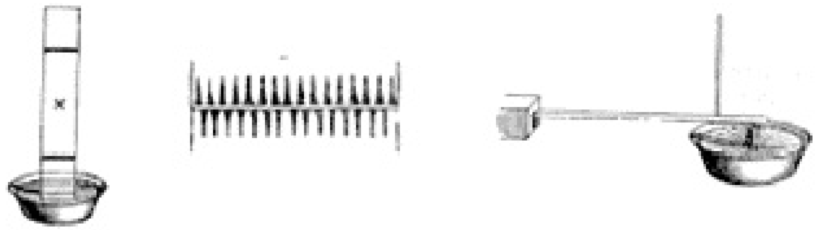

Figure 5. Faraday's diagrams showing the vibrating lath oriented vertically (Left) with a top view of the ridged crispations appearing perpendicular to the lath's blades and on both sides (Center). When the lath is aligned horizontally and vibrating vertically so as to immerse a cork extender in the water, these ridges radiate outward from the cork (Right) (Faraday 1831b, pp. 352-354).

this, he laid fine lycopodium powder over a drumhead surface.[14] His conjecture was confirmed when a powder cloud arose having "a misty honeycomb appearance . . . alternate portions rapidly expanding and contracting simultaneously" ([1831b] 1991, §125, pp. 356–357).

Faraday's final Diary entry on crispations is not another experiment, but an amazing natural observation made on holiday at the beach:

> 146. Remarked a peculiar series of ridges produced by action of steady strong wind on water on sandy shore . . . ridges were formed *parallel* [my emphasis] to the direction of the wind . . . continually reciprocating . . . When the water deepened enough to form waves then these ridges disappeared. They are small and require carefull looking for . . . (*Diary,* 18 July 1831, §146 (1932, vol. 1, p. 358)).

Faraday expanded on the ridges' meaning in his published paper. These were no ordinary wind-blown waves; the direction of the wind was wrong for that. While ordinary waves break up the ridges, layering oil on wavy water (to still the waves) may bring them back. Faraday speculated that, like crispations, these ridges arose under an "oscillatory condition" of the water as a body, perhaps provoked by "the elastic nature of the air itself" ([1831b] 1991, §122, p. 356).

This condition of oscillation represents a way of thinking about the phenomena different from traveling wave propagation. For us, it expresses a field idea of a vibrating state sustained throughout the whole space of the fluid (for another example of Faraday's use of something other than electromagnetism to infer field behaviors, see Tweney, this volume). Some-

14. Wheatstone (1823) attributed to Ørsted the innovative use of lycopodium powder (club moss spores) in Chladni figures; see Ørsted 1807.

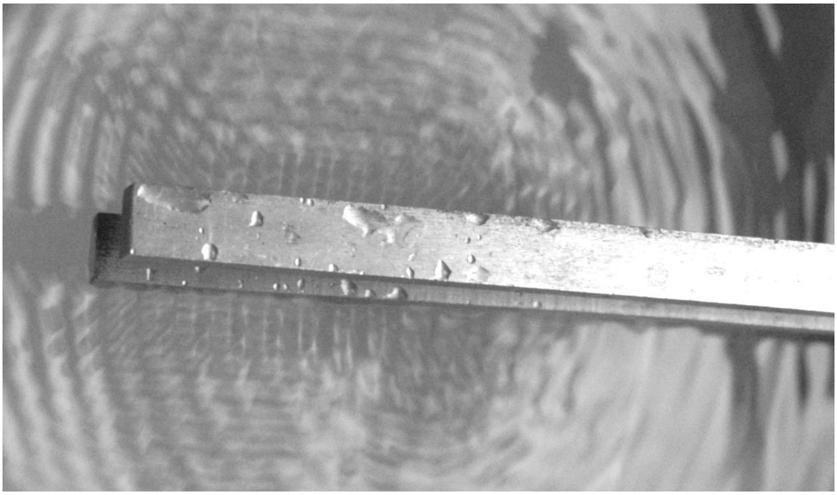

Figure 6. Ridge waves appear in water, perpendicular to the tuning fork's tines. Photo by James Bales, MIT Edgerton Center, using a Nikon D-100 at a shutter speed 1/160s, f6.3, focal length 40mm.

thing like this spatial sense was arising in Faraday's experimenting and thought. However, his language in the paper does not make clear how this underlying thinking is distinct from ordinary wave analysis.[15]

In reading Faraday's experiments and comments, I was thoroughly confused. Implicitly I assumed the crispations were strictly longitudinal transmissions from the glass plate's bottom. Faraday's vertically suspended lath experiment did not make sense to me. Eventually the oscillatory condition emerged for me. This took numerous rereadings to deepen trust in Faraday's observations—and seeing the ridges myself, with a large tuning fork oriented at all angles to the water's surface (Figure 6).[16]

The crispations were not merely wondrous and strange; for Faraday their analysis portended something much more pervasive in nature's ways. His paper's concluding remarks divulge a clue. He perceived this oscillatory condition set up within a medium as analogous to light. In this context, Faraday discussed Fresnel's inference, founded on work with polarized light, that light consists of vibrations that are transverse to its ray

15. The crispations effect is nonlinear, and unlike the behavior of the more familiar linear waves.

16. My experience of personal confusion, and trust in Faraday's observation, is analogous to Crawford's efforts to understand Faraday's work with lateral electric currents (1985).

direction (Faraday [1831b] 1991, pp. 357–8). Fresnel portrayed the vibrations of ordinary unpolarized light as equally distributed among all azimuthal angles in the transverse plane.[17] For Faraday, crispations explicated how this could be:

> 128 . . . Now the effects in question seem to indicate how the direct vibration of the luminous body may communicate transversal vibration in every azimuth to the molecules of the ether . . . ([1831b] 1991, §128, p. 358)

Although light was not the ostensive subject of the crispations paper, or the extensive subsequent research by which Faraday developed evidence for the action of "lines of force" in space, light was latent within all of it. This came out fifteen years later when Faraday was pressed to speak unprepared. Spontaneously he expressed a "bold" tentative conjecture that light is a vibration subsisting in these lines—without need for an ether:

> The kind of vibration which, I believe, can alone account for the wonderful, varied, and beautiful phenomena of [*light's*] polarization, is not the same as that which occurs on the surface of disturbed water, or the waves of sound in gases or liquids, for the vibrations in these cases are direct, or to and from the center of action, whereas the former are lateral. ([1846] 1991, p. 370)

In ruling out ordinary sound and water waves as a model for light and presenting instead arguments for his lines of force, Faraday did not allude to his own early study of this behavior—in the crispations. Yet through it, he had developed flexibility and coherence in experimenting and understanding that continued across his subsequent work in ways that deepened, extended, and reorganized what he knew about the world. Tweney (1992) has identified the crispations' fleeting nature as preparatory to Faraday's detection of the subtle and transient electromagnetic induction of currents, made in the following month. The discussion presented here suggests that the crispations also contributed to his longterm investigations of fieldlike properties in nature.

An Infant's Search Becomes Persistent, and is no longer Fooled

Piaget's close following of his infants is like Faraday's crispation study in just these ways of flexibility and coherence. More is going on than trials of

17. When Faraday mentioned Fresnel by name, but not by explicit citation, in [1831b] 1991, pp. 357–8, it may be that he refers to a Fresnel paper containing a similar (but non-identical) passage to Faraday's quotation (included in Fresnel 1866, vol.1, p. 636 and referenced by Wheatstone 1823).

what water and babies can do; something is emergent in their experimenting and thought that sustains its conduct and persists into later work. For Piaget, the infant's evolving search is reflexive of all activities where experimenting and thought restructure our relation with something other.

Piaget was always improvising to keep things fun and unexpected as the children grew. His hiding games became more complex. When a child could retrieve a toy put under any cover, he placed it sequentially under one cover, then another, and left it under a third (as I did with Summer). Early on in this game, the child looked only under the first cover; after the child went straight to the last hiding place, Piaget introduced yet another twist. He placed the watch in his closed hand (or a box), then while both these were under cover, secretly left the watch inside the cover and removed only the empty hand or box. Immediately, the child opened the exposed box or hand.

In a series of trials, Jacqueline (at 18 months) showed interest in the cover (obviously bulging around something), but raised it only when her dad left the box (with object) underneath. Then she recovered both box and watch. Even upon many repetitions, she did not suspect that the object remained behind the empty hand; she could not infer its invisible transferal. Piaget researched this further by passing a ring from one hand to the other, and then offering Jacqueline both closed hands. Initially, she opened only the first hand. Upon more trials, she opened the first one—and then the other (he switched the hands' order). Later that same day, she went right to the final hand. And, after a few tries, she directly found the ring when father had slipped it under his beret.

Piaget regarded even this success as incomplete; his constructive thinking about development moved him to seek fuller logic in his daughter's actions. Jacqueline's practical actions still lacked awareness that, whether she sees it or not, something might be displaced and yet still be found no matter where. A month later, a slight of hand still could still fool her to look in a false intermediate hiding place. Piaget termed this apparent regression a "décalage," where some subtlety in the task (such as the invisible transfer) evokes a new reorganization or relearning of all the actions and inferences that were previously worked out in a less taxing case (such as the game with sequential hiding places). Perhaps we see an example of décalage when Faraday used the tuning fork to redo his vibration strength tests, and reorganize what those showed with his prior experience. To Piaget, Jacqueline's behavior also suggested that object and child remained dependent on each other: "for the child, the object is not yet entirely what it is for us." (Piaget [1937] 1964, p. 78)

Nearly a month later, Piaget broached yet more complicated hiding maneuvers—and Jacqueline responded with new systematicity. He passed a pencil concealed in his hand among three covers—always in a different order—and left it under the last. The little girl applied her search to the last cover, often directly, sometimes after first touching the others in the order of the hiding. Piaget saw these successes as more than chance. Her hesitations, where she mentally reviewed the pencil's itinerary, bespoke a new cognitive dimension. Nor was she forestalled when the pencil was enveloped in multiple coverings, such as a box inside the beret under a cover. Jacqueline got past all obstacles; even when the small box slipped under something, she "continues looking for it, evidently convinced of its presence". (Piaget [1937], p. 81) The child grasps the pencil in relation to herself and other things in space and time. She has constructed it as an independent persisting object in an environment of other objects.

Now the child, who was the subject of Piaget's experimenting, has become an experimenter herself. Having come into relation with things other than herself, she explores what they are like and conducts real experiments and genuine searches to find out. The story of her development is "a process of learning which should not be considered as either purely experimental or purely deductive, but which partakes simultaneously of experience and mental construction." (Piaget [1937] 1964, p. 95) This very process bears out the coherence in action and thought both of *his* interactions with the children, and of his evolving understandings of development.

The process of development showed itself to be flexible, responsive, and generative of novelty—of new ways of being in the world. While observed here during an infant's sensorimotor period—preceding the acquisition of language—Piaget's further researches involved children of all ages. Piaget saw this process being "recapitulated" again and again as the child's frontier activity moves from coordinating physical motions, to linguistic communication, to formal reasoning. Each passage of development involves the child in restructuring its relations with the world (Inhelder and Piaget [1955] 1958, p. 342).

The Experimenter's Dialogue

This process does not cease when the maturation of adolescence is complete. Piaget was commenting on Gruber's study (1974), following Darwin's thinking on human evolution through musings recorded in private notebooks, when he wrote:

> . . . as the ideas are interdependent with each other and also with previous ideas which have guided even the discovery of the

> observables, every alternation at one point gives rise to a modification of the system as a whole. This process maintains both the coherence of the system and at the same time the adequacy of its fit to the data of experience and observation. (Piaget [1974] 1981)

Yet these words might also be taken to describe how Piaget and Faraday each worked out new understandings as their emerging ideas continually deepened in coherence through experimental dialogue with the world.

5. Conclusions and Educational Implications

Considering Piaget and Faraday side-by-side, we reach a startling conclusion. While Piaget was studying infants, his method is applicable to physics, and is almost precisely that of Faraday in investigating a multitude of phenomena as an inseparable whole. Likewise, Faraday's responsive tuning of experimental parameters mimics Piaget's playful variations in perceptual experiments. This "open-ended" study—in both cases—involved the learner (Faraday or Piaget) in a process of continually improvising ideas and interventions with something other. Self-taught through generating their own questions, Faraday and Piaget both made learning and self-development inextricable. Their thinking centered not upon externally imposed rigor, but instead welled from playful immersion, where variation perpetually arises from curiosity and interplay between human and materials. What each did in experimenting was play in the profound sense of wonder about the world.

While such curiosity comes naturally to young children, my work with adult teachers shows that it is never outgrown. However current science instruction does little to tap into that natural curiosity or to midwife lifelong commitments to experimenting and learning. The key to learning this process is to begin it. By describing these explorative processes, this paper prepares groundwork for bringing the "open inquiry" methods of Faraday and Piaget to science learners.

By contrast, current science instruction largely employs "closed-ended" inquiry directed at answering externally generated questions. Ethnographic and interview studies of high school science classrooms uncover a prevailing "cookbook approach" to labs (Roth 1994, p. 197) where the students' task is to produce results already presented in lecture. One student contrasted the circularity of laboratory exercises with genuinely seeking the unknown:

> . . . it's not experimenting . . . where you're experimenting to find out what's going to happen . . . it's experimenting to make that happen (Hughes-McDonnell 1996 p. 30).

Science education construed as equipping students with correct science language and models leaves scant room for observations originating with students. Even in "hands-on" or "inquiry" curricula, lab activities are often pre-structured in steps tailored to remediate student failings and bring them around to a conventional understanding (see McDermott 1991, 1996).

These methods of instruction leave personal questions unanswered and perhaps even unvalidated. As a result, many students—especially, but not only, women—are convinced that science is exclusive and denies them admission (Campbell, Dennes and Morrison 2000, McDonnell 2005). In science classrooms where experimentation evolves through students' curiosity and observing, their learning becomes self-generating, joyful and resilient (Schauble, Glaser, Duschl, Schulze and John 1995, Hammer 1996, Hughes-McDonnell 2000, Sconier 2000, Cavicchi 1999, 2005). The legacy of Faraday and Piaget is that anyone—even infants—can initiate science explorations; all it requires is patience, perceptiveness, and a commitment to understand.

Just as light was more often a latent, than explicit, subject of Faraday's research, so were the prospects of an education informed by research on child development, for Piaget. Piaget's occasional speculations about education were analogous to Faraday's on light—and share with his in being tentative, thoroughly grounded in experience, and presciently visionary. Observing that the developing child already possesses curiosity along with intellectual and practical capacities sufficient for genuine experimenting (Piaget [1969] 1972), Piaget advocated letting that activity become the means of education:

> Let us therefore try to create in the school a place where individual experimentation and reflection carried out in common come to each other's aid and balance one another. (Piaget [1932] 1965, p. 404)

Faraday's insights about light have engendered much in today's technology—with uses for health and harm. What human benefits might ensue if we were to act as seriously on Piaget's insights—and Faraday's example—about experimenting as a means of learning?

References

Abbott, Berenice 1986. "Berenice Abbott: The Beauty of Physics", Hank O'Neal, New York NY: The New York Academy of Sciences.

Baillargeon, Renee and Julie DeVos 1991. "Object Permanence in Young Infants: Further Evidence." *Child Development,* 62: 1227–1246.

Besson, Thomas, W. Stuart Edwards and Laurette Tuckerman 1996.

"Two-frequency parametric excitation of surface waves." *Physical Review E,* 54: 507–513.

Burian, Richard. 1997. "Exploratory Experimentation and the Role of Histochemical Techniques in the Work of Jean Brachet, 1938–1952." *History and Philosophy of the Life Sciences,* 19: 27–45.

Butterworth, George. 1977. "Object Disappearance and Error in Piaget's Stage IV Task." *Journal of Experimental Child Psychology,* 23: 391–401.

Campbell, George. Ronnie Dennes and Catherine Morrison 2000. *Access Denied: Race, Ethnicity, and the Scientific Enterprise.* Oxford UK: Oxford University Press.

Cavicchi, Elizabeth. 1997. "Experimenting with magnetism: Ways of learning of Joann and Faraday." *American Journal of Physics,* 65: 867–882.

———. 1999. "Wires, Batteries, Bulbs and the Induction Coil: Narratives of Teaching and Learning Physics in the Electrical Investigations of Laura, David, Jamie, Myself and the Nineteenth Century Experimenters—Our Developments and Instruments." Dissertation, Harvard University, Cambridge MA.

———. 2003. "Experiences with the Magnetism of Conducting Loops: Historical Instruments, Experimental Replications, and Productive Confusions." *American Journal of Physics,* 71(2): 156–167.

———. 2005. "Exploring Water: Art and Physics in Teaching and Learning with Water." in *Facilitating Watershed Management: Practical Approaches and Case Studies,* Edited by Robert France, Lanham MD: Rowman & Littlefield.

Crawford, Elspeth. 1985. "Learning from Experience." Pp. 211–227 in *Faraday Rediscovered: Essays on the Life and Work of Michael Faraday, 1791–1867,* Edited by David Gooding and Frank A. J. L. James, New York NY: Stockton Press.

———.1993. "A Critique of Curriculum Reform: Using History to Develop Thinking." *Physics Education,* 28: 204–208.

Duckworth, Eleanor. (1987). 1996. *"The Having of Wonderful Ideas" and Other Essays on Teaching and Learning.* New York NY: Teacher's College Press.

———. 2001. *"Tell Me More": Listening to Learners Explain.* New York NY: Teacher's College Press.

Edwards, W. Stuart and S. Fauve. 1993. "Parametrically Excited Quasicrystalline Surface Waves." *Physical Review E,* 47: R788-R791.

———. 1994. "Patterns and quasi-patterns in the Faraday experiment." *Journal of Fluid Mechanics,* 278: 123–148.

Faraday, Michael. (1831a). 1991. "On a Peculiar Class of Acoustical Figures; and on certain Forms assumed by groups of particles upon vibrating elastic Surfaces." Pp. 314–332 in *Experimental Researches in Chemistry and Physics,* London: Taylor & Francis.

———. (1831b) 1991. "On the Forms and States assumed by Fluids in Contact with vibrating Elastic Surfaces." Pp. 335–358 in *Experimental Researches in Chemistry and Physics,* London: Taylor & Francis.

———. (1846) 1991. "Thoughts on Ray Vibrations." Pp. 366–372 in *Experimental Researches in Chemistry and Physics,* London: Taylor & Francis.

———. 1932. *Faraday's Diary: Being the Various Philosophical Notes of Experimental Investigation.* Edited by Thomas Martin, London: G. Bell and Sons LTD.

Fresnel Augustin. 1866. "Considerations Mécaniques sur la Polarization de la Lumiere." Pp. 629–653 in *Œuvres Completes D'Augustin Fresnel,* Paris: Imprimirie Impériale.

Gooding, David. 1981. "Final Steps to the Field Theory: Faraday's Study of Magnetic Phenomena, 1845–1850." *Historical Studies in the Physical Sciences,* 11: 231–275.

———. 1985. " 'In Nature's School': Faraday as an Experimentalist." Pp. 105–135 in *Faraday Rediscovered: Essays on the Life and Work of Michael Faraday, 1791–1867.* Edited by David Gooding and Frank A. J. L. James, New York NY: Stockton Press.

———. 1990. *Experiment and the Making of Meaning: Human Agency in Scientific Observation and Experiment.* Dordrecht: Kluwer Academic Pub.

Gratch, Gerald and William Landers. 1971. "Stage IV of Piaget's Theory of Infant's Object Concepts: A Longitudinal Study." *Child Development,* 42: 359–72.

Gruber, Howard. (1974) 1981. *Darwin on Man: A Psychological Study of Scientific Creativity.* Chicago IL: University of Chicago Press.

Hammer, David 1995. "Student Inquiry in a Physics Class Discussion." *Cognition and Instruction,* 13: 401–430.

Höttecke, Dietmar 2001. "Die Nature der Naturwissenschaften hisorisch verstehen. Fachdidaktische und wissenschafteshistorische Untersuchungen." Dissertation, University of Oldenberg, Germany.

Hsueh, Yeh. 1997. "Jean Piaget, Spontaneous Development and Constructivist Teaching." Dissertation, Harvard University, Cambridge MA.

Hughes-McDonnell, Fiona. 1996. "Understanding High School Physics Students' Perspectives of Their Classroom Experiences and Their Images of Physics and Physicists." Qualifying Paper, Harvard Graduate School of Education, Cambridge MA.

———. 2000. "Circuits and Pathways of Understanding: 'I can't believe we're actually figuring out some of this stuff.'" Dissertation. Harvard University, Cambridge MA.

Inhelder, Bärbel and Jean Piaget. (1955) 1958. *The Growth of Logical Thinking from Childhood to Adolescence: An Essay on the Construction of Formal Operational Structures.* New York NY: Basic Books Inc.

———. (1959) 1964. *The Early Growth of Logic in the Child.* New York NY: Humanities Press.

Ippolito, Maria and Ryan Tweney. 1995. "The Inception of Insight", in *The nature of insight,* R. J. Sternberg and J. E. Davidson, eds., Cambridge MA: MIT Press.

Jackson, Myles W. 2006. "Harmonious Triads: Physicists, Musicians and Instrument Makers in Nineteenth-Century Germany." Unpublished book manuscript.

Kuhn, Thomas. (1964) 1977. "A Function for Thought Experiments." Pp. 240–265 in *The Essential Tension: Selected Studies in Scientific Tradition and Change,* Chicago IL: University of Chicago Press.

Kurtz, Elke and Ralph Hertwig. 2001. "To Know an Experimenter" in *The Essential Brunswik: Beginnings, Explications, Applications,* Eds. Kenneth Hammond and Thomas Steward, Oxford: Oxford University Press, 180–186.

Lifschitz, Ron and Dean Petrich. 1997. "Theoretical Model for Faraday Waves with Multiple-Frequency Forcing." *Physical Review Letters,* 79: 1261–1264.

McDermott, Lillian. 1991. "Millikan Lecture 1990: What we Teach and What is Learned—Closing the Gap." *American Journal of Physics,* 59: 301–315.

———. 1996. *Physics by Inquiry: An Introduction to Physics and the Physical Sciences.* New York: Wiley.

McDonnell, Fiona. 2005. "Why so Few Choose Physics: An Alternative Explanation for the Leaky Pipeline." *American Journal of Physics,* 73: 583–586.

Müller, Hans. 1994. "Model Equations for Two-Dimensional Quasi-patterns." *Physical Review E,* 49: 1273–1277.

Ørsted Hans Christian. 1807. "On Acoustic Figures." Pp. 261–2 in *Selected Scientific Works of Hans Christian Ørsted,* Trans. and edited by Karen Jelved, Andrew Jackson, Ole Knudsen, Princeton NJ: Princeton University Press.

Piaget, Jean. (1926) 1964. *The Child's Conception of the World.* London: Routledge & Kegan Paul Ltd.

———. (1932) 1965. *The Moral Judgment of the Child.* London: Routledge & Kegan Paul Ltd.

———. (1937) 1964. *The Construction of Reality in the Child.* New York NY: Basic Books.

———. (1941) 1965. *The Child's Conception of Number.* New York NY: W. W. Norton & Co.

———. (1946) 1970. *The Child's Conception of Time.* New York NY: Basic Books.

———. (1948) 1967. *The Child's Conception of Space.* New York NY: W. W. Norton & Co.

———. (1969) 1972. *Science of Education and the Psychology of the Child.* New York NY: Viking.

———. (1974) 1981. "Foreword." Pp. vii-ix in *Darwin on Man: A Psychological Study of Scientific Creativity,* by Howard Gruber, Chicago IL: University of Chicago Press.

Piaget, Jean and Bärbel Inhelder. (1948) 1967. *The Child's Conception of Space.* New York NY: Norton.

Piaget, Jean, Bärbel Inhelder and Alina Szeminska. (1960) 1981. *The Child's Conception of Geometry.* New York NY: Norton.

Ribe, Neil and Friedrich Steinle. 2002. "Exploratory Experimentation: Goethe, Land, and Color Theory." *Physics Today,* 55 July: 43–49.

Roth, Wolff-Michael. 1994. "Experimenting in a Constructivist High School Physics Laboratory." *Journal of Research in Science Teaching,* 31: 197–223.

Schauble, Leona, Robert Glaser, Richard Duschl, Sharon Schulze and Jenny John. 1995. "Students' Understanding of the Objectives and Procedures of Experimentation in the Science Classroom." *The Journal of the Learning Sciences:* 4: 131–166.

Sconier, A. D. and J. L. Rosiek. 2000. "Historical Perspective as an Important Element of Teacher's Knowledge: A Sonata-Form Case Study of Equity Issues in a Chemistry Classroom." *Harvard Educational Review,* 70, 370–404.

Steinle, Friedrich. 1996. "Entering New Fields: Exploratory Uses of Experimentation." *Philosophy of Science* 64: S65-S74.

Tweney, Ryan. 1992. "Stopping Time: Faraday and the Scientific Creation of Perceptual Order." *Physis* 29: 149–164.

———. 2002. "Epistemic Artifacts: Michael Faraday's Search for the Optical Effects of Gold." In *Model-Based Reasoning: Science, Technology,* *Values,* Edited by L. Magnani and N. J. Nersessian, New York NY: Kluwer Academic.

Weber, Ernst H. and Wilhelm Weber. 1825. *Wellenlehre auf Experimente gegründer.* Leipzig: Gerhard Fleischer.

Wheatstone, Charles. 1823. "New Experiments on Sound." *Annals of Philosophy,* N.S.6: 81–90.