Epistemic Artifacts: Michael Faraday’s Search for the Optical Effects of Gold

RYAN D. TWENEY

'Department of Psychology, Bowling Green State University, Bowling Green, OH, USA

Abstract: In 1856, Michael Faraday (1791-1867) carried out an extensive program of research to explore the properties of thin films of metallic gold. Such films had long been of interest to him because they possess the peculiar property of appearing gold in color by reflected light, but green by transmitted light. Faraday hoped this behavior would model the general interaction of light and matter, perhaps extending his earlier finding that magnetic fields could affect a beam of polarized light passing through a highly refractive substance. In the course of this work, Faraday prepared over 600 microscope slides with thin metallic films adhering to them. Most of these epistemic artifacts have survived, as have his extensive diary records. Examination of this material permits reconstruction of his successive attempts to create a kind of dialogue with nature and provides evidence for his sophisticated ability to interactively create a microverse that could expand his mental microverse of field lines of force. While he failed to achieve his larger goals, the surviving specimens constitute a series of increasingly articulated representations of the structure of metallic matter. The case is thus one in which the “model” converges with the very thing intended to be modelled.

1. INTRODUCTION

Michael Faraday’s (1791-1867) research has served as the source for a number of interesting case studies that reveal the extent to which his research relied upon model-based reasoning. There is now little doubt that understanding his strategies of experimentation and theorizing requires appreciation for his construction, evaluation, and use of models. Thus, Gooding (1990) explored Faraday’s 1821 experiments on the rotation of current-carrying wires in a magnetic field and replicated the constructive processes, the “makings,” that went into Faraday’s discovery of the phenomenon. In this work, Faraday gradually moved from the vaguest of construals to a fully-formed mental model of the tangential character of electric and magnetic forces. Similarly, Nersessian (1984; 1985) showed how Faraday’s emerging notion of field was developed over time and later extended by Maxwell using a model-based approach to elaborate the laws of electromagnetism.

In the present paper, I explore the model-based reasoning of Faraday along dimensions that have previously received little attention. In particular, I give an account of his constructive making of physical specimens in a microscopic domain. In this way I bridge the gap between accounts of mental models, as such, and in which the mental models are intertwined with physical models. In effect, I open inquiry into the nature of epistemic artifacts, a term suggestive of a merging of recent work on “cognitive artifacts” (e.g., Hutchins, 1995; Zhang & Norman, 1995) and “epistemic things” (Rheinberger, 1997).
Nersessian (1999) noted that traditional accounts of science have been excessively “propositional” and hence have been restricted to the linguistic expression of results. As one consequence, many analysts have felt that any account of discovery processes was “merely” a psychological question. Yet, as Magnani (2001) and others have argued, discovery processes can be analyzed under the general heading of “abduction,” that is, as processes which emphasize the creation of hypothetical explanations, rather than just their justification once formulated. Magnani’s notion of “manipulative abduction” is especially relevant in the present case.

To be sure, Faraday’s gold research, like most of his other research, reflects cognitive processes that are now often used to describe in vivo scientific thinking. Thus, uses of analogy are present, imagery is extensive, much of the record could be interpreted as search through a problem space, and Faraday can be seen as struggling to develop new classifications (see, e.g., Andersen, 2001; Dunbar, 2001; Gentner, et al., 2001; Gorman, 1997; Langley and Jones, 1988; Nersessian, 1999; Tweney, 2001). Yet none of these processes taken singly can fully capture the way in which Faraday interacts with the materials and objects of his laboratory to shape his model construction activity. In the present paper, I hope to show how such interactions can be studied, and their implications for understanding scientific activity in general.

1.1 Light, Matter, and the Field in Faraday’s Time

For Faraday, the 1840s and 1850s represented a period of consolidation of his field theory (Nersessian, 1985). Faraday himself had played an important role in the transition from earlier simply “materialistic” conceptions of the ether to the characteristic British accounts that followed the mid-century, accounts that emphasized the imponderable character of the ether (Cantor and Hodges, 1981). These later accounts emphasized the continuous character of the ether, and its special status — if the ether was “matter,” it was matter of a very peculiar sort. Faraday had not taken direct part in earlier debates about the undulatory theory of light, perhaps because many of the relevant papers were mathematical in character, and, as is well known, he did not use (or perhaps even understand) the formal mathematical methods characteristic of a George Gabriel Stokes or William Thomson (see Gooding, 1982; Williams, 1965).

As James (1985) has shown, Faraday was committed in many ways to an “Optical Mode of Investigation,” using optical criteria, for example, in his development of the distinction between diamagnetic and paramagnetic substances, and manifesting a long-standing concern with whether or not there was an ether. Chen (2000), in examining the role of instruments in optics during the 1800s, distinguished between a “visual tradition” in optics, in which the eye played an intrinsic role (and the wave vs. particle dispute was secondary), and a “geometric tradition,” in which instruments were used to both generate and detect optical effects, and in which the wave vs. particle issue was paramount.

From an early date, Faraday felt that the optical behavior of metals was an important domain in which to learn about the nature of light and matter. His 1845 discovery of magneto-optical rotation, the rotation of the plane of polarization of light when a magnetic field is applied to a highly refracting medium, suggested that a unified account of light, electricity, magnetism, and matter might be possible. After 1845 he emphasized how important it was to understand the interaction of field forces with the material substrates within which they were manifested (Fisher, 2001). His research on diamagnetism (part of which was also optical) served to solidify Faraday’s account of the lines of electric and magnetic force as physical lines of force (Faraday, 1852). Thus, by 1856, convinced of the reality of physical lines of force in the electric and magnetic domains and committed to a hunch that light might be similar, Faraday reopened his “ancient query” of gold’s interaction with light (Faraday, Diary, 14722, 21 April, 1856, in Martin, 1936, p. 108).
1.2 Situating Faraday: The Problem of Gold

The research carried out in 1856, the focus of the present paper, occurred toward the end of Faraday’s productive career. In this year, Faraday actively explored the action of matter on light. From the outset of the program, partly conducted using microscopical techniques, he sought to examine the optical effects of thin films of metal (primarily gold leaf) on light. Faraday began by asking a deceptively simple question: Why does gold leaf appear to be yellow by reflected light but green by transmitted light? This question had appeared in Faraday’s 1822 “Notes” (Tweney and Gooding, 1991). His renewed interest in the question in the 1850s may have been partly stimulated by the discovery of fluorescence by George Gabriel Stokes (1852). Stokes argued for a “resonance” account to explain the emission of visible light when certain substances were illuminated by invisible ultraviolet light. His explanation was related to Faraday’s conjecture that light must involve “transverse” vibrations (i.e., across the line of propagation) as well as the longitudinal vibrations characterized by the known wavelength and frequency of light (Faraday, 1846).

Faraday began his 1856 program (which lasted almost a year) by using a powerful achromatic microscope at Warren De la Rue’s laboratory to examine commercial gold leaf. This merely confirmed the limits of microscopical vision; one can see holes in gold leaf at all magnifications, but the resolution of even the finest microscope was simply too limited to reveal whether the structure of the leaf was continuous or whether the holes continued “all the way down.” If the holes did continue downward, then the transmitted light colors could conceivably be a diffraction effect.

Using procedures first developed by De la Rue, Faraday explored ways of making films that would be thinner than commercial gold leaf (which is made by mechanical means, by hammering gold to thin it). In the process of making thin films by chemical means (first with De La Rue and then in his own laboratory), Faraday noted a “ruby colored fluid” that seemed to be generated when gold salts were reduced by phosphorus to make gold films. These fluids possessed rather remarkable properties, as Faraday soon discovered. In particular, he soon characterized what later became known as the “Tyndall Effect” (or, more properly, the “Faraday-Tyndall Effect”), namely, that the fluids scattered light in a fashion similar to that of suspensions of particulate matter. Unlike other suspensions, however, the fluids did not settle with time. Today, Faraday’s work is most often remembered for this; he is acknowledged as the discoverer of metallic colloids.

During the subsequent months of research Faraday prepared hundreds of thin films, dozens of colloids, and a variety of other specimens as well. Although the program was largely unsuccessful in terms of its major theoretical goal, to integrate the interaction of light and matter with Faraday’s developing ideas about electrical and magnetic fields, nevertheless, the discovery of gold colloids, the Faraday-Tyndall Effect, and Faraday’s explorations of the molecular-level interactions of particles and light, were important outcomes. The research culminated in what was to be Faraday’s last major publication in the Philosophical Transactions (Faraday, 1857). Sadly, later investigators (particularly Zsigmondy, 1909) mischaracterized what he did achieve in this work, and it has continued to be regarded (except by colloid chemists!) as “minor.”

1.4 The “Discovery” of Faraday’s Gold

Recently I was privileged to “discover” the surviving specimens used by Faraday in his 1856 research on gold. In fact, it has long been known that some of his colloids survive in the collections of the Royal Institution of Great Britain, where Faraday worked and lived during his entire career; these colloids are frequently mentioned as proof of the longevity of colloidal suspensions. Yet it had not been noted that over 600 other specimens also survive, mostly in the form of thin films of metal deposited on ordinary 1” x 3” microscope slides (Tweney, 2000). The surviving films are mostly gold, but also include silver, platinum, palladium,
copper, and other metals. Each slide was numbered (by Faraday) and keyed to reference lists in his Diary entries covering the period of his research on gold (Martin, 1936; the gold research is recorded in entries 14243 to 15403, dated February 2, 1856 to December 20, 1856, pp. 11-254). Because of his careful indexing, we know that nearly all of the specimens are preserved. The combined Diary and specimen collection is one of the most complete records in existence of the work of a great 19th century scientist.

Together with the Diary, the surviving specimens allow us to see deeply into the processes of Faraday’s constructive scientific thought, even given his characteristically thorough records. Metallic films (especially gold films) are inherently stable and non-reactive, so we can be sure the specimens remain much as they were in Faraday’s time. Furthermore, it is possible to reconstruct our own versions of many of the specimens, permitting insight into the dynamics of the physical and chemical makings used by Faraday, and allowing us also to redo many of his manipulations (destructive and otherwise) of the specimens. One could not ask for a more complete “thought record!”

The present paper previews our work with this material. Currently, we are photographically documenting many of the surviving specimens with an eye toward creating an “enhanced” diary, one in which the reader can access not only Faraday’s textual comments about his work, but the images associated with it as well. In addition, we are beginning to recreate some of the chemistry used by Faraday, and we are working to prepare slides and colloids that resemble the originals. In the present paper, I give a brief account of some of our preliminary results and suggest ways in which these results may contribute to further understanding of the role of epistemic artifacts in the development of mental models.

2. FARADAY’S STRATEGY OF RESEARCH

There is now little dispute over the nature of the complex optical properties of gold and other metals; these can be explained as the outcome of the interaction of light and the free conducting electrons that constitute the defining characteristic of metals (Hecht and Zajac, 1974; Tilley, 2000). In Faraday’s time, however, metals constituted a serious puzzle for scientific accounts of matter. One of Faraday’s concerns was whether metals were continuous material substances or particulate in nature. Since Faraday did not accept the view of matter as composed of hard material particles (“Daltonian atoms”), he was disposed toward any evidence that gold was continuous and not particulate, and he actively sought such evidence in the 1856 research.

Yet how can the continuity of a film be established? The principal strategy used by Faraday was to explore the optical properties of thin transparent metallic films, particularly of gold. At the outset, he knew that commercial gold leaf was far thinner than the wavelength of light, and he was able to prepare films that were even thinner. Yet, if the films are so thin and still affect light, an explanation is needed for how that could happen. Thus, the colorful transmitted light appearance of gold could be due to diffraction effects caused by extremely small holes in the film. In ordinary gold leaf, such holes are visible at all magnifications, even at ones approaching the limit of resolution of a light microscope. Could even smaller holes be causing the colors? This hypothesis is present in the text of 1822 “Notes” and is probably not unique to Faraday. Yet, as noted, he began his 1856 research by using De la Rue’s state-of-the-art achromatic microscope to examine gold leaf – without success.

2.1 Faraday’s Chemical and Optical Approach

Following his inconclusive microscopical examination of gold leaf, Faraday pursued other strategies for attacking the issues. It is clear that he spent a fair amount of time planning his program of research, since the first Diary entries (dated 2 February, 1856) lay out a series of queries to be answered, along with notes of his observations at De la Rue’s a few days earlier. In these initial notes, Faraday ponders both the theoretical issues and the specific procedures that might be used to obtain thinner and more regular films of gold. He
also laid out a plan to examine precipitates of gold and gold salts, and to compare these to films produced electrolytically and chemically. In the end, electrochemical deposition never worked for Faraday as a means of preparing such films, and so chemical means were used in most of the research.

Preparation aside, how are such films to be studied? Both physical and chemical manipulation played a large role here. Faraday subjected his slides to extensive treatment by acids, bases, heat, pressure, and even “boiling in oil” to determine their properties. Of special note are the many optical explorations he carried out. Does gold leaf polarize light? Can it refract light and hence act as a lens? What is the relation between the reflectivity of such films and their transmitted light color? Over time an inquiry that began with films alone interrelated both films and fluids, raising fundamental questions about the possible states of matter.

2.2 The 1856 Program

Almost at the beginning of his work with the gold films, in the course of preparing films by using phosphorous to reduce gold chloride, Faraday noticed the “ruby red fluid” produced as a byproduct of “the mere washing” of the equipment (Diary, section 14321, 6 February, 1856, in Martin, 1936, p. 22). This serendipitous remark initiated a new focus in his research, to investigate these ruby-colored fluids. Many others had noticed such fluids in connection with the reactions of gold (e.g., they were described by Samuel Parkes, 1822), but Faraday was the first to describe their connection to the appearances of metallic films, and he was probably the first to closely examine them. As soon as he began to make the fluids deliberately, he found that some were blue or purple (rather than red) and that blue and purple fluids were more subject to rapid settling. Using an optical technique (described in Faraday, 1827) to examine whether these fluids were suspensions, he found that even the ruby ones, which did not settle and appeared clear, would disperse light when a thin beam of sunlight was passed through them. The fluids were indeed a puzzle; like solutions, they appeared clear and did not settle over time, but, like suspensions, which do settle, they dispersed light.

Two kinds of specimens thus formed the focus of his program, thin films and the very interesting “fluids.” The similarities and the differences in the color of such specimens intrigued him; both films and fluids could be red, blue, or purple by transmitted light, but only films ever appeared green.

By the beginning of March, 1856, Faraday had convinced himself that the films and the fluids were both gold in an uncombined state. He then turned to a more intensive examination of the properties of each, looking in part for ways to quantify the thickness of his films. This problem was never solved directly (other than to establish that the phosphorous films were much thinner than commercial gold leaf). Thickness of the films was an important variable at this stage; could the varying color of deposited films of gold be due to varying thickness? He tested this option by depositing multiple films on the same slide, arranging them in a “staircase” fashion, thus a gradually increasing change in thickness could be seen in one view. The results were clear; while the amount of light transmitted became less with increasing thickness, there was no change in the hue for a given kind of film. Thickness alone did not account for the color.

Using an agate burnisher to subject the films to high mechanical pressure, Faraday found that he could turn a blue or purple film into a green film, suggesting that the mechanical disposition of the particles of the film had something to do with their color. By the end of March he knew that the color of most films could be destroyed by heat (made into a gray, generally) but that a green color could be restored by burnishing. He then turned to a more intensive examination of the color of the ruby fluids.

The fluid colors were also mutable; the red fluids seemed most resistant to settling, but they could be changed to blue or violet fluids by certain chemical agents (which did not react chemically with the gold), as
well as by heat. Was heat therefore changing the nature of the gold particles? Their size? Their shape? And if the fluids indeed manifested the optical effects of particulate gold, are the similar colors produced by the films also the result of particles of gold? Or are the films really continuous (non-particulate) in character?

In April, Faraday attacked the question of particles in a more direct fashion, first by showing that thin gold films on glass do conduct electricity (implying their continuity), and then by “deflagration,” that is, by exploding gold wires using sudden currents of electricity (Wilkinson, 1804, had described this technique, as part of a larger work on “galvano-electricity”). When wires are exploded in proximity to a glass slide, a colorful deposit of gold can be left on the slide; such specimens are arguably particulate in character (most do not conduct electricity, for example), and yet they show a similar range of color as the thin films, and they exhibit clear metallic reflections, just like the films. By the 21st of April, he was determined to find whether the ruby fluids were in fact red, blue, or purple because of the influence of multiple particles on the transverse vibrations of light. Accordingly, he carefully constructed a prism apparatus that allowed him to separate a narrow band of the spectrum of sunlight into a thin beam of nearly monochromatic light. Using this, he examined “Very many of the films” (14722), as well as the ruby fluids. The results merely confirmed what the unaided eye had already told him; that the films and fluids absorb some colors and transmit others, but there was no evidence that the specimens were directly changing the color of light, as seemed to occur in fluorescence when “Stokes’s Ray” (ultraviolet light) was changed into visible light.

In May and June, Faraday concentrated upon careful observations of the color of slides and films (and, to a lesser extent, of dried precipitates). He also evaporated some of the colloids, noting that these also show metallic reflection. The inquiry now appeared broader; the problem of color was not restricted to the transmitted color, but also involved reflected metallic color. Remarkably, evaporated colloids and exploded wire deposits both showed metallic reflections — and he was increasingly sure that both were particulate. Thus, even the metallic color of a metal may be due to an interaction among particles and light!

Relatively few entries occur for July of 1856, but they are important ones, since Faraday reached the conclusion that the green appearance of films is due to the presence of elongated particles. And in August and the first part of September, concentrating his attention on the ruby fluids, he carefully explored the chemical properties of the fluids, ruling out the possibility that the colors were a product of dissolved salts or any substance other than metallic gold. At the same time, he sought to understand why some of the fluids are blue and some red. Once again, was it size of particle? Or shape? The results suggested to him that size was the important factor here; blue fluids have larger particles than the red.

In October, Faraday carefully sought to characterize the optical properties of films and fluids in polarized light. At the beginning of the program (in February), Faraday had established that films of gold did not affect a polarized ray of light sent through them. Warren De la Rue later informed Faraday, however, that he had found an effect if the film was inclined at 45° to the beam of polarized light. Glass will act the same way, however, so is the effect due just to the glass? Or are the films alone sufficient? Needless to say, it is difficult to mount so thin a film across an open space, but Faraday (and De la Rue) finally succeeded in doing so. In addition, Faraday worked out a way to optically remove the optical effect of the glass by immersing a glass-mounted gold film in carbon disulfide, which has the same refractive index as glass. Glass “disappears” in such a fluid and no longer rotates a polarized beam, even when tilted. But the gold films, now mounted on “invisible” glass, still rotated a polarized ray, as did the particulate deposits from exploded gold wires. There were now at least two strong grounds (rotation of a polarized beam and the metallic reflection of dried colloids and exploded wire deposits) for asserting that the interaction of light with separate particles is responsible for optical activity, even in films. And, most importantly, Faraday’s model of the
interaction of light with gold now manifested a true field effect; color is produced when a light beam traverses an array of particles; that is, color is something that happens between particles!

By the end of October, Faraday still believed that green is the true color of “continuous” gold, and that red and blue are the true colors of “divided” gold. Alas, however, he could not, in the end, prove this, since all of the evidence was indirect, and he could never “see” the particles directly, nor could he rule out other factors in all of the cases. By November he knew that the chemistry is very complex, that the reaction kinetics (to use a modern term) are similarly complex and diverse, and that mechanical effects can occur at a very small scale. Thus, since green happens only when some mechanical force operates to elongate otherwise symmetrical particles, the obvious conclusion would seem to be that all color effects in gold are due to field effects among particles. Still, Faraday was cautious in phrasing the conclusion; “[This] would seem to imply that the particles are so small and so near, that two or more can act at once upon the individual atoms of the ether. Their association is such as to present as it were an optical continuity” (Faraday, 1857, p. 439).

Faraday’s research on gold ended abruptly in December, 1856, and there are no further entries dealing with gold after this date. In February, Faraday read a paper to the Royal Society (published as Faraday, 1857). He characterized the results almost apologetically; “I do not pretend that [the results] are of very great value in their present state, but they are very suggestive” (p. 393). In March, 1857, Faraday took up the completely different problem of “time in magnetism.”

3. REPLICATING FARADAY

The value of replications as a means to historical understanding has been established by a number of studies. Our own attempts to replicate Faraday’s work have so far been “opportunistic” rather than systematic, insofar as we have had to learn skills that, for Faraday, could be taken for granted. Among other things, we have had to work under the constraints of modern safety regulations and procedures. Thus, Faraday’s most important method for producing thin films of gold, the reduction of gold chloride by the phosphorous vapor found over a carbon disulfide solution of phosphorous, has not yet been attempted (both carbon disulfide and phosphorous are extremely hazardous materials!)

We have succeeded in producing gold colloids that closely resemble Faraday’s by using a modern method (reducing a weak solution of gold chloride with sodium citrate solution). These produce an excellent dispersion effect and constitute a replication of the discovery of the Faraday-Tyndall Effect. When evaporated, the colloids produce slides and watch glasses having the same metallic reflective colors that struck Faraday as noteworthy.

In replicating some of his chemical manipulations we have used aqua regia to thin a glass-mounted gold leaf, and, in the process, verified Faraday’s observation that such chemical action does not in itself change the green color of such films. We have also noted some of the unusual morphology that can emerge from such treatment, in particular, a strange array of connected block-like “cells” that Faraday referred to as the “Chinese Wall.”

Our friend and associate, Harry Brown, of Jackson Mississippi, has also produced a thin gold film by reducing dissolved dental gold using dextrose. This exceptionally thin film displays a blue color by transmitted light and an apparent continuity under the microscope that closely resembles some of Faraday’s slides. The film does not adhere well, however, and we have not been able to repeat Faraday’s burnishing of such slides since the film simply rubs off. Producing such films is also highly unreliable using “soft” reductants like dextrose; we now know why Faraday relied upon the phosphorous method!
At present, as we accommodate to the hazardous materials that we will need to use eventually, we are beginning experiments to “deflagrate” metallic wire with sudden surges of electricity. This also has been a trickier project than we had first imagined, and makes clear why Faraday went to the expense and bother of using a “Grove’s Cell” for these experiments, an acid battery using zinc and platinum electrodes, characterized by very low internal resistance (Grove, 1839). When we tried a variety of lead acid batteries (commercial automobile storage batteries), we found that their internal resistance was so high that the resulting slow discharge across a thin wire merely melted the wire instead of exploding it. Since then, and given the huge expense of recreating a Grove’s Cell, we have set up a large capacitor bank driven by a standard laboratory power supply. When the capacitors are fully charged they discharge rapidly across the thin wire and produce a satisfying “explosion.” Copper wires deflagrated in this manner resemble the kinds of deposits seen by Faraday, and we are beginning the same experiments with pure gold wire, obtaining slides which also resemble Faraday’s specimens.

Our replication work is still ongoing, but it has already served to “open” many aspects of the Diary to our view. Photography of the slides is alone helpful in this regard, since much of the Diary text relies upon verbal descriptions of what Faraday saw. Good though his Diary descriptions are, they are necessarily incomplete as records of this overwhelmingly visual domain; accordingly, much time has been devoted to photographing some of the surviving specimens, and we are beginning to create a “digitized” version of his Diary that will be enhanced with appropriate images.”

Clearly, however, the replications can carry us even further; if photographs open the Diary text by adding the visual elements, replications open the processes by which the visual objects of the text were constructed. These successive openings have revealed just how much the original Diary record is telegraphed and incomplete.

4. CONCLUSION – EPISTEMIC ARTIFACTS

The larger goals of the present project are centered on the process of uncovering the interactive strategies used by Faraday in his research on gold, thus situating the research more carefully in the context of its time and as an important episode in Faraday’s own career. In addition, there are implications that are relevant to understanding the general nature of model-based reasoning.

Our “hands on” work replicating the procedures used by Faraday to produce his specimens has the promise of uncovering his tacit skills and knowledge. As we proceed with the work, more and more of the Diary text becomes transparent to us. Until we had begun the replication work, much of the Diary was puzzling; “Why did he do this?” “Why didn’t he do that?” The value of our replications is thus similar to the value of thought experiments in science; like thought experiments, replications assist in the reconstruction of an argument (Nersessian, 1999), noting, of course, that the argument is one we are making. By contrast, only some of Faraday’s constructive practices were intended to aid argument construction; in fact, most of his work was not finished enough to permit a final argument to be constructed. Instead, Faraday was most often using constructive practices and the resulting objects to either pose a question or ask a question. Each slide was an element in a dialogue between Faraday and the world of gold.

In casting the specimens as elements in a dialogue, I mean to call attention to two related points. First, as Fisher (1992) noted, Faraday’s “voice,” even in his published writings, was highly dialectical in the sense that questions were posed, tentative answers given, new questions raised, and so forth. As the gold project makes clear, this is especially true when Faraday is uncertain of the outcome of his work; even in the end, the specimens were as much questions as they were answers. Faraday’s goal, unfulfilled here but present in all of his research, was to make nature legible (to use Fisher’s, 2001, term), that is, to allow something like
a direct reading of the nature of nature from his specimen preparations. In this case, he succeeded only partially.

The specimens are more than just discursive elements; they are *epistemic artifacts*. They are “epistemic” insofar as they participate in the discourse; things can come to be known by means of the artifacts. And they are “artifacts” because they are made by Faraday as parts of that discourse; he is an *agent* in their construction (Kurz and Tweney, 1998). Much of science reflects a similar use of “preparations,” of course, but note that several important distinctions need to be considered. First, *cognitive artifacts* (Hutchins, 1995; Zhang and Norman, 1995) are computational artifacts which can lead to new results but do not lead to new knowledge (except in the restricted sense that the outcome of a computation is new information). Second, Rheinberger’s (1997) *epistemic things*, which do lead to new knowledge, differ from Faraday’s preparations in that they were constructed to serve as a consensually agreed means used by a community of scientists; they are finished products. By contrast, Faraday’s specimens are mostly private objects; only a very small fraction ever became publicly known, and only a few, even for Faraday, represented anything like a finished, unambiguously legible, object. Instead, most of his slides were rather like the construals noted by Gooding (1990) or the “inceptions” discussed by Ippolito and Tweney (1995; see also Tweney, 1992) in that they remain vague and unformed as carriers of meaning. Legibility emerged only after long series of artifacts, arguments, and experiments had been deployed.

It has long been noted that Faraday’s universe was “force-centered,” in that force was given priority over matter as a fundamental physical construct (Cantor, 1991; Williams, 1965). In my view, even Faraday’s “ways of knowing” (Cavicchi, 1997) are force centered; for him, one came to know the world partly by making the proper epistemic artifacts. In similar fashion we seek to make Faraday’s model-based world of gold films and ruby fluids legible to us.

**ACKNOWLEDGEMENTS**

Initial work on this project was supported by a grant from the British Academy, (sponsored by the University of Bath), and by NSF #SES-0100112, awarded through Bowling Green State University. I am deeply grateful to the staff of the Royal Institution Center for History, Science, and Technology, London, and especially to Frank A.J.L. James, Reader in History and Philosophy of Science, and Keeper of the Collections, at the RI. Without his enthusiastic support, this project could not have been conducted. My laboratory work on the replication experiments was assisted by Ryan Mears and Andy Wickiser, and I have had the benefit of chemical and photographic advice from Harry Brown and Tom Grill.

**REFERENCES**


Graham, T., 1861. Liquid diffusion applied to analysis. Philosophical Transactions, 151, 183-224.

Grove, W., 1839. On a small Voltaic battery of great energy, Philosophical Magazine, 15, 287-293.

Hecht, E. and Zajac, A., 1974, Optics, Addison-Wesley, Reading, MA.


1 It has been suggested (Williams, 1965) that Faraday was working with “diminished capacity” at this stage of his life, implying perhaps that the research on gold should be taken as uncharacteristic of his full ability to understand nature. At the present stage of my investigation, however, I can see no evidence that any of his 1856 research was affected in such a way. This issue will be addressed at a later date.

2 De la Rue (1815-1889), an accomplished microscopist, is best known for his photographic expertise, having made stereo photos of the moon and sun in 1861. He had long corresponded with Faraday (James, 1999; Williams, 1971).

3 Thomas Graham (1805-1869) first coined the term “colloid” (Graham, 1861).

4 Later the same year he published a two-page “Note on the irregular fusibility of ice,” (Faraday, 1858,) in the same journal, as a comment on a longer work by John Tyndall.

5 An account of these disputes is beyond the scope of the present paper; see Roscoe and Schorlemmer, 1886, for a relevant historical overview that still reflects uncertainty about the nature of metals.

6 The characterization of Faraday’s program given here is necessarily very sketchy. A complete account should also discuss his inquiry into the reflective and transmissive properties of other metals, his work on gels, his work on the color of organic substances stained by gold, and – of most relevance in the present context – Faraday’s reports of his visits to craftpersons, e.g., goldsmiths, gold beaters, and scientific instrument makers. In addition, his own skill as a bookbinder meant that Faraday had a long acquaintance with gold leaf and gilding processes. All of these aspects must be ignored here, but will be dealt with in future publications.

7 For example, he found that the lateral pressure of a slowly dissolving phosphorous particle floating on a fluid was sufficient to create at least some green areas in the films that form around the phosphorous particle.

8 For example, the papers in Blondel & Dörries (1994), especially that by Heering (1994), suggest that Coulomb’s experimental determination of the law of electrostatic attraction and repulsion could not have been carried out as Coulomb described it.

9 Some of the images can be seen at my web site, which will also include links to the digitized Diary, when this is complete; [http://personal.bgsu.edu/~tweeney](http://personal.bgsu.edu/~tweeney).

10 For similar views on the value of replication, see Cavicchi, 1997; Kurz & Hertwig, 2001; and Gooding, 1990.