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On Replicating Faraday:
Experiencing Historical Procedures in Science

Ryan D. TWENEY[a]

Abstract

A variety of replications of Michael Faraday's research on the optical properties of gold are described and related to recent uses of replication in cognitive historical research. Replication as a historical tool is here treated as an aspect of the experiences of the historian, rather than of the scientists whose historical practices are the focus.

Keywords: *Faraday, Replication, Cognitive-Historical, Optics, Chemistry of Gold*

Introduction

> "We young ones have a perfect right to take toys, and make them into philosophy, inasmuch as nowadays we are turning philosophy into toys"
>
> Faraday, *Chemical History of a Candle*, 1861

In this quote, made during the first of his demonstration lectures on the nature of a candle flame to a "juvenile" audience, Michael Faraday (1791-1867) expressed at once an attitude toward science ("philosophy" was the more common term then) and an attitude toward the means by which knowledge is both acquired and used. For Faraday, things and their manipulation were just as important to the development of new knowledge, as knowledge was to the development of new things and new manipulations.

Faraday's demonstration lectures followed in the rich tradition of other lecturers at the Royal Institution where he lived and worked; Thomas Young, William Brande, and, of course, his mentor, Humphry Davy, whose compelling theatrical demonstrations made his lectures a society favorite (Taylor 1988). Even so, a new element appears to have characterized Faraday's approach to the lecture demonstration, and it is nowhere more evident than in the 1860-61 series on the "Chemical History of a Candle."

Manipulation was the very soul of science for Faraday; no empirical generalization, no "mere hypothesis," no theoretical concept could be sustained until it was manifested and manipulated in the laboratory. Much has been written about his scientific practices, practices that remain stunning examples of the power of experimentation, especially as an aid in the construction of new knowledge (see, for just a few examples, Cavicchi 1997 and this issue; Gooding 1990; Steinle 2003; Tweney 1985). Faraday's lecture demonstrations showed a similar spirit; his audience's knowledge was enhanced by seeing (not merely hearing about) the science, and he constantly encouraged audience members to "try this at home."

In the present paper, I report on a series of experiences, not Faraday's but my own and that of my students. These experiences build on our own right "to take toys, and make them into philosophy." In this case, the "toys" were replications of Faraday's procedures (that is, models of prior practices, "toys" for scholars), rather than apparatus as such. The sought-for "philosophy" was the historical-cognitive understanding of scientific practices, instantiated here in Faraday's work, but applicable across many domains. In the present paper, it is not the "philosophy" that is the focus, rather it is the "toys," or, more precisely, the play that we made with them. I use the term "play" carefully, partly just to emphasize the fun we had, partly to emphasize what is inherent in **all** historical replication. There is always, especially at the beginning, a novice quality (leading to a degree of expertise), a clumsiness (leading to skill), an ignorance developing into new knowledge and understanding. The scholarly results of our replications have been reported elsewhere (e.g., Tweney 2006). The present paper reports the personal side.

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Background: Faraday's "Old Problem" of Gold

By 1856, when Faraday took up the specific research that is our subject, he was near the end of his career. His field theory of electricity and magnetism had reached its final form, as far as he was concerned, and was being extended by Maxwell, Thomson, and others whose mathematical approaches were foreign to Faraday (Gooding 1981, Nersessian 1985). Returning to what he called his "old problem" of the colors of gold, Faraday spent most of 1856 in trying to extend his theory toward an exploration of the interaction of light and matter, using an "optical mode of investigation" (James 1985).

Fig. 1. A 3" x 3" gold leaf mounted on glass by Faraday. The light source is on the right. Reflected light is gold in color while that transmitted through the leaf is green. Courtesy of the Royal Institution.

Gold was the place to look for such extensions for several reasons. In particular, because of its malleability, gold is the only metal that can be beaten into films so thin they are actually transparent. Further, such films show some remarkable color effects: when light reflects off the surface of such a film, it has the familiar yellow-gold, shiny, appearance. But when light is passed through the film, the color is usually green (Fig. 1). In what way did the substance of the leaf actually interact with light? Could this be a clue about the nature of light? The nature of matter?

On both fundamental questions, Faraday was undecided (although he certainly had presuppositions). Faraday himself had been, a few years earlier, the first to show that light was affected by the presence of a magnetic field, the first empirical step towards the later identification (by Maxwell) of the electromagnetic nature of light. As for matter, Faraday had never been a Daltonian atomist. That is, he did not accept the theory that all matter was composed of identifiably distinct fundamental particles. For him, this was a purely speculative claim, still in need of proof. Since gold leaf was matter in what appeared to be a continuous state, could its interaction with light be a way to identify whether the substance of gold leaf was in fact continuous?

In the end, Faraday did not succeed in meeting these large goals, but the research had two important consequences nonetheless: It led him to the first preparation of metallic colloids and to the discovery of the "Faraday-Tyndall Effect," the scattering of light by a colloid.

Finding Faraday's specimens

The Royal Institution of Great Britain (the "RI") in London holds a rich treasure-trove of Faraday's writings, apparatus, even some of the furniture he used. The RI today is both archive and library, but it is also a working scientific laboratory, the oldest continuously operating lab to still reside in the same building. For that reason, there are "survivals" among its holdings that could well have perished had the lab ever moved; odd bits of things not clearly identified but saved only out of a sense of loyalty to the past.

Among these odd bits is a large collection of microscope slides and other specimens, made by Faraday during 1856 as part of the project on the colors of gold. It was exciting to identify these, hidden, as they were, "in plain sight." They were part of a museum display recreating, with many of Faraday's instruments, what his "magnetic laboratory" might have looked like (Fig. 2)

A few years ago, I noticed some interesting looking boxes in the display (Fig. 3). When, with the help of Frank James, the Curator of the Archives, these were removed and examined, they proved to contain more

Fig. 2. The Museum area at the RI, a mockup of one of Faraday's labs. The slides are in the boxes at far right. Photo courtesy of the Royal Institution.

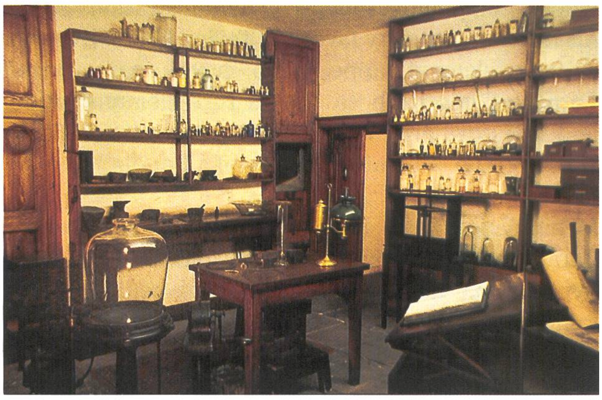


Fig. 3. Some of the boxes of microscope slides preserved by Faraday. Courtesy of the Royal Institution.

than 700 microscope slides, and a few hundred related specimens, all carefully numbered and indexed by Faraday. These specimens were the key to understanding how Faraday had worked during the project (Tweney 2002). Faraday kept hundreds of pages of notes about this research, and these have long since been published and studied (Martin 1936), but they remained rather opaque until it was possible to read the notes with the specimens at hand. In effect, the specimen set was **part** of the Diary itself. It was no more possible to fully understand his notes without the specimens than it would have been to understand his notes by reading every other word!

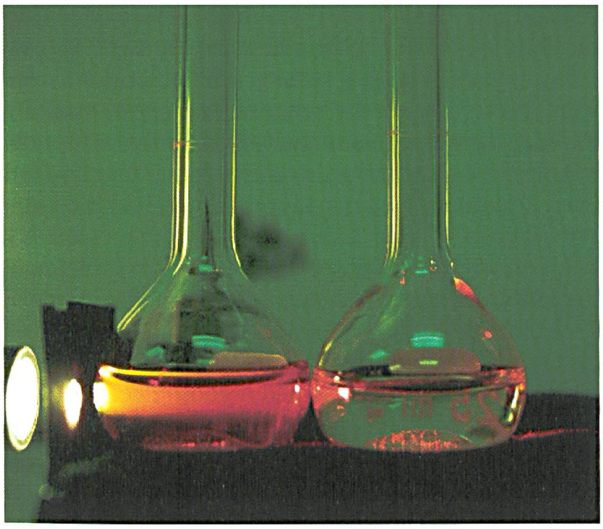
Having the Diary + Specimens made possible a better reading of the whole, but it was also, in some respects, still frustrating. For one thing, while nearly all of the microscope slides used were present, there were many missing specimens of other types. Faraday's research led to the first identification of what we now call "metallic colloids" (suspensions of nano-sized metallic gold particles in water), but, except for a very few in the RI collection, these are usually unstable and mostly did not survive. More importantly, for every question that appeared answered about the meaning of the project as a whole, other questions arose, and most of these were procedural. **How** did Faraday do this? **Why** did he use an apparently expensive procedure to do that? What happened during **this** experiment to lead him to try **that** experiment? It was not long before we had to embark on a series of replications to fill out what our new understandings told us would be still more complete, if supplemented by replications. We sought not just Diary + Specimens, but Diary + Specimens + Procedures.

Making Colloids

To begin, we sought to obtain some colloidal gold preparations, to give us at least some inkling of what was the major outcome of Faraday's 1856 research, the first such preparations (he did not use the term, "colloid," coined a few years later by Thomas Graham). Gold colloids can be obtained commercially, but we opted instead to prepare our own, using a modern technique. By dissolving a gold chloride in water (about which see below), and gently heating it with sodium citrate solution, we prepared a "ruby fluid" (as he called it) whose properties resembled those described by Faraday (Fig. 4)

If the chemistry was unremarkable (and unhelpful in providing insight into what **Faraday** did), the exercise was an important preliminary step for our later historical replications. For one thing, we were forced to become familiar with modern standards for the safe use, handling, and disposal of chemical substances. We were granted space to store materials in a histology lab used by the neuroscience program in the Department of Psychology at Bowling Green, and we had shared access to the usual lab equipment, including two fume hoods, proper sinks, an eye wash fountain for accidents, and a variety of first aid and emergency equipment. Quite unlike Faraday's lab, of course, but essential to us nonetheless!

Fig. 4. One of our "citrate" gold colloids (left), and a solution of gold chloride (right). The narrow beam of light shows the "Faraday-Tyndall Effect" on the colloid but not the solution.



In addition, and perhaps most importantly, we had to navigate the institutional realities of our use of this shared space. This entailed some overt bureaucratic procedures (gaining permission from the Animal Safety Care Committee, for example, and obtaining key codes for the locked facility), but it also required learning the "etiquette" of the lab – when to claim priority over use of the fume hood, for example, and what bits of glassware or standard chemicals could be "borrowed" without permission and which were "hands off." Like any modern lab, there is a complex network of implicit rules, a non-obvious hierarchy of knowledge and expertise (e.g., some students know aspects of procedure and techniques that no or few faculty members seem to share), and even favorite time windows – mornings were best for us, since few neuroscientists seem to be early risers!

Learning to make colloids forced us to review and relearn long-forgotten procedures – using a magnetic stirrer, making solutions, cleaning glassware (somehow my student assistant became better at this than I, there being hierarchies among our group as well as among the neuroscientists), the proper way to mix and/or dilute concentrated acids (always pour the heavier one slowly into the lighter one – there's a reason why the specific gravity is printed on every acid label), even such simple tasks as pouring from one vessel to another (use a stirring rod, to prevent drips). We felt ourselves to be in a "chemical kindergarten" at times, and often felt foolish when things went awry. Still, the skills were important to us, and many of them had not in fact changed since Faraday's time – witness his textbook, "Chemical Manipulation" (1827), an important guide to our procedures.

Precipitating Gold

Following our success with preparing colloids, we were rather cavalier about our first true historical replications. Our ultimate goal was to make ultra-thin deposits of gold on glass slides, as Faraday had, by using phosphorous to reduce gold chloride. These were, in fact, almost the very first specimens made by Faraday (using a technique learned from a friend), but he was, after all, an experienced chemist – and even he actually began in his own lab by making some precipitates of gold and examining their color. My students and I, by contrast, were working with only dimly remembered college and high school courses, and, except for the colloid preparations, none of us had actually worked with gold compounds or phosphorous. Precipitates seemed a good place to begin because of their simplicity; just react a solution of gold chloride with a solution of iron sulfate, and metallic gold should precipitate out. This was old knowledge even in Faraday's time, so we at first thought these must have been "warm up" exercises for Faraday, as they were intended to be for us. We later concluded otherwise – there was a strategy to Faraday's choice of where to begin, but it was not evident to us until later.

Having by then a small grant to purchase chemicals and supplies (NSF 0100112), we ordered some further gold chlorides from a chemical supply house. Ah, but **which** gold chlorides? There are two generally available commercially, Gold (I) Chloride and Gold (III) Chloride; we tried both. Of course, Faraday used neither term, for him "gold chloride" was, well, just that, and he referred only to a "standard solution of gold chloride."[1] Further, we had found that dissolving our expensive gold chlorides in water was problematic. They just wouldn't dissolve without leaving a sediment (some sediment is visible above in Fig. 4 at the bottom of the right-hand flask). We ignored this when making colloids, but the point of the precipitate replications was to obtain insoluble gold alone, so we had to be sure that the sediments were produced only by the reduction of the gold chloride. Worse yet, gold chlorides are hygroscopic, absorbing water from the atmosphere, thereby changing their appearance, color, and solubility. Eventually, we learned that the modern understanding of "gold chlorides" involves a lot that was not available to Faraday; the differing valence states of gold, for example, or the understanding that, even in solution, gold chlorides can manifest different states depending upon the amount of water involved (Puddephatt 1978). In effect, there is no such thing as a "simple" gold ion (Au^{+++}, say) in solution with simple Chloride ions (Cl^-).

Faraday made no mention of such complexities, noting simply at one point that he dissolved gold in Aqua Regia to make Gold Chloride. Even I remembered from school days that Aqua Regia is the only acid that will dissolve gold, so we hunted up the "recipe" and made some. Mix hydrochloric acid and nitric acid in the right proportions, stir, and you have a powerful gold-dissolving brew. Indeed, some gold wire (bought for another purpose, see below), dissolved very rapidly in the stuff, turning the liquid a bright gold-yellow color. As Faraday would have, we boiled this for hours, adding water as needed, until we could detect no further fuming. This apparently drives off the reaction byproducts and any residual acids. Whatever remained was our "Gold Chloride." We did not fully understand what products could really be in the flask, but our uncertainties on that

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[1] Crystalline "Gold Chloride" (not otherwise identified) was available commercially at least by 1866, when Joseph Griffin & Sons offered "pure crystals" at the rather princely sum of 78 Shillings per ounce (Griffin 1866).

point could not have been different from Faraday's. The real test was whether we could obtain precipitates like his.

In contrast to his description of preparing gold chloride, he was very explicit about the Iron Sulfate used as a reagent. Here, there was no uncertainty and we were able to follow his procedure exactly; what he referred to as "Protosulphate of Iron" corresponds exactly to "Ferrous Sulfate," and, barring the change in terminology, the understanding is the same. Iron Sulfates do not have the complexities of "Gold Chlorides"! Since Faraday indicated the quantities involved, we were even sure we had the same concentration that he used.

Our reward was a series of precipitated gold preparations. Phenomenologically, these were often puzzling, the exact appearance depending on many factors (temperature, concentration, whether or not stirring is used as the iron sulfate solution is added, and so on). Still, the usual result was a cloudy precipitate, usually brown or yellow, that settled within minutes.

In the course of our "play" with precipitates (recalling that we hadn't expected much beyond a refinement of our technique), we had an unexpected insight. When we shone a light at the preparations (following Faraday), we noted the scattering from the macroscopic particles of precipitated gold. This reminded us of the "Faraday-Tyndall Effect," the scattering of light by the microscopic particles of a colloid. Our recently prepared colloids being at hand, we could see the similarity. Placing a colloid, a solution, and a precipitate in a row, we passed a beam of light through the three, and the "family resemblance" of the colloid and the precipitate became clear (Fig. 5). And this, in turn, led us to realize that what we **recognized** was exactly what Faraday had **noticed**.

Fig. 5. From left to right; the "ruby fluid," a gold chloride solution, a gold precipitate.

Interestingly, Faraday never explicitly mentioned in the *Diary* that he had placed all three of these preparations in a row, as we had, but it was now easy to understand that he must have had at least a mental picture of the three together, and that it was this family resemblance that led him to take up the question of exactly what was going on in the scattering of light by the colloid, which otherwise looks like a solution (Tweney et al. 2002).

Faraday's next step, however, was not to immediately explore the light scattering properties of his "ruby fluids," but rather to examine more closely the thin gold films deposited on glass that he had made with the help of his friend, Warren De la Rue. Alas, we had not yet identified the proper friend to come to our aid for these experiments, so we turned instead to another series of replications – and another series of frustrations.

Deflagrating gold

As noted earlier, Faraday's interests in the colors of gold were part of a larger concern with the potential continuity of transparent matter. Faraday was not an atomist in the strict sense, and gold was the only truly transparent metal, so its optical properties were a logical place to look; unlike glass and other transparent materials, gold could occupy a variety of states – thin sheets, small particles (as in precipitates and colloids), in solution, and so on. Gold manifested a variety of spectral colors. Did these depend upon its state, or merely its chemical combinations? If particulate, did gold's color depend on size? Were there essential differences between sheets and particles?

One approach he used was based on an old and well-known technique in which thin gold wire was "deflagrated" (i.e., "exploded" or "vaporized") by passing a quick current through the wire. There was a consensus that the resulting deposits on a glass slide held near the point of deflagration were particles, not continuous deposits. A close examination of these deposits followed Faraday's first inklings that the "ruby fluids" were suspended particles too small to see even with a microscope.

We initially attempted replications of Faraday's procedure using a few automobile storage batteries and thin gold wire, but the best we could do was to melt the wires, or, in some cases, the alligator clips we used to hook up the wire to the battery. Clearly, the wire has to be the thinnest part of the circuit, and hence the highest in resistance, so we began replacing alligator clips with heavier assemblies, still to no avail – melt the wire, yes. Vaporize it? No.

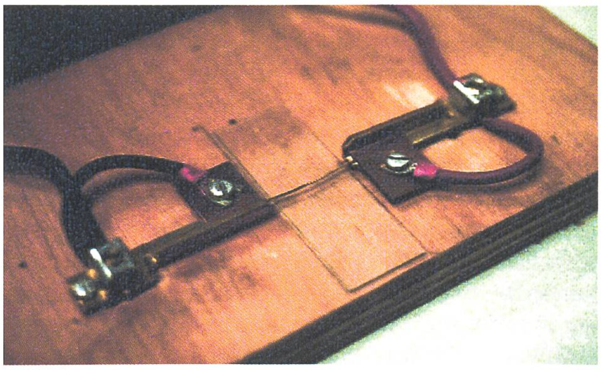
The Psychology Department employs a full time electronics and electrical engineer, Andy Wickiser, and it was Andy who really worked out the solution. The auto batteries were clearly not appropriate, probably because they possessed way too much internal resistance. Faraday used a battery of multiple "Grove's Cells" as his first source of current. A bit of research disclosed that this was a platinum cell, noted for its low resistance, but clearly also an expensive solution, one way beyond our means to replicate (Mills 2003). In his later deflagrations, he switched to a battery of multiple Leyden jars, each charged by an electrical machine (a Wimshurst device). In fact, in the days before readily available chemical cells (like the Grove's Cell), this was the standard procedure (see Wilkinson, 1804, and the discussion in Tweney et al. 2005).

Fig. 7. One of Faraday's "deflagrations" (No. 321, Faraday's numbering). Courtesy of the Royal Institution.

As a substitute, Andy constructed a battery of modern capacitors, charged by a bench top power supply. With a large knife switch to enable a rapid onset of current, and leads made out of copper bar for low resistance (Fig. 6), we managed to vaporize the gold wire at last! A satisfying pop, a white flash, and an extensive gold deposit could be had, bonded to a nearby microscope slide. While the slide sometimes came apart under the force of the explosion, and often showed traces of glass damage, along with bits of apparently solidified molten gold, the main deposits had the same characteristic appearance as Faraday's.

The colors were amazing! As in Faraday's specimens (Fig. 7), we had successfully replicated the full range of colors he had seen: red, blue, purple, traces of green here and there. Further, our slides, like his, had a metallic sheen, visible when the slide was held edgeways, and the deposits were mostly transparent as well. Here was a clear case where definite particles of gold were producing the same effects as what appeared to be continuous sheets of matter. Could those sheets, the thin films of gold leaf which first caught his attention, be particulate as well?

Fig. 6. Our deflagration apparatus. The gold wire (center) is mounted above a glass slide.



Gold ... and phosphorus

At the very beginning of his Diary notes on gold, Faraday recorded a visit he made to his friend Warren De la Rue, well-known for his work in the new techniques of photography. De la Rue had been experimenting with thin films of gold as a coating for telescope mirrors, and he was able to show Faraday how to make such films, thinner than the thinnest commercially available gold leaf. The technique involved using elemental phosphorous to reduce a gold chloride solution, leaving a thin film of gold floating on the surface of the chloride solution.

Faraday was very explicit about the method he used:

> "Have been this morning to De la Rue's to learn his mode of making the films of Gold—is as follows. A piece of phosphorus about this size [a circle about 1 cm in diameter was here drawn] is dissolved in about 30 minims[2] of Sulphuret of carbon to form one fluid P—a solution of Gold free from acid and containing about a sovereign in 2 or 3 ounce volumes forms the second fluid G. A clean plate of flat glass about 5 inches square—a glass capsule 6 inches in diameter—a large Wedgewood's dish holding 3 or 4 quarts

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[2] A minim in modern measure is about 0.06 ml, hence 30 minims is a little less than 2 ml.

> of water—some strips of flat glass-card board, polished copper, etc. A little of the phosphorus solution P was poured into the glass capsule and moved over its surface to distribute the phosphorus—most of the sulphuret of carbon evaporated. A portion of the gold solution G was poured on to the **clean** [emphasis in original] glass plate—spread over its surface by a glass rod—the excess quickly poured off at one corner back into the bottle, and then the wetted plate inverted and placed over the phosphorus in its capsule; gradually a film of gold formed which could be recognized by reflected light because of its colour and appearance. Then the glass plate was turned up and, being brought over the dish of water, was inclined a little to the horizon and depressed until one edge and gradually the whole was under water—the metallic film floats; if well made it is stiff and does not change in form by the surface currents of the water—if badly made it moves about as a film of oil on water, there being little or no cohesion of the parts. A piece of glass or of card being immersed in the water—brought beneath the film and raised, brings up the film with it, and then bibulous paper can be used to dry up the water and leave the film on the glass" (Diary, Feb. 2, 1856, Para. 14319. In Martin 1936).


Fig. 8. Phosphorous

For our purposes, this was wonderfully explicit, even the concentrations and sizes of the reaction vessels are specified! Replicating the procedure should be straightforward. That proved to be the case as far as the chemistry was concerned, but there were other difficulties we had not anticipated, mostly having to do with the phosphorous.

Elemental phosphorous exists in two common allotropes, white and red, differing chemically only in molecular structure, but having wildly different properties. The red version can be obtained commercially but is relatively unreactive and is useless as a reducing agent for gold. The white version is what Faraday used. It is highly flammable and will in fact ignite spontaneously in air, for which reason it is kept under water until needed. Alas, it cannot be purchased commercially (except by licensed weapons manufacturers, given its use in incendiary explosives!) because of its alternative use as a reducing agent in the preparation of some illegal drugs. The replications we sought to do would have to be carried out with an "unobtainable" substance!

Faraday's "Sulphuret of carbon" is today known as Carbon Disulfide (CS_2) and is commercially available, although it too is highly flammable and toxic. We were able to purchase this, but drew a blank in trying to purchase the white phosphorous. Eventually we were given some, purchased long ago (when still legal) by a then - high school student for use in home experiments (Fig. 8). Alas, we still faced the problem of using these dangerous substances in a safe and yet historically revealing manner. We needed help!

Lawrence Principe is Professor of Chemistry and of the History of Science at Johns Hopkins University in Baltimore. He is well known for his work on the history of early chemistry, especially an important book on Robert Boyle (Principe 1998). As part of his research on the transition from "alchemy," to "chymistry," to "chemistry," he conducted a series of replications of early modern alchemical procedures, including much work on metallic gold. Principe generously shared his knowledge and skills and, during a three day visit to Baltimore, showed me how to prepare the films as Faraday had.

In fact, the chemistry was simple and straightforward, but it was Larry's skill that made this apparent. His expertise saved me much grief, time, and money. Some of his skills constitute a kind of practical knowledge hard to obtain except with long experience. Thus, I had been dissolving expensive gold wire in Aqua Regia; he suggested instead that Canadian gold dollars, which are 99.99% pure gold (one of the few world coinages still made that way), would be the cheapest source. So, a gold Canadian coin was the source of the highly saturated gold chloride solution needed for the replications! Remembering that Faraday himself had used a gold sovereign (see above), this was actually an appropriate move, and quite possibly a necessary one, since the gold chloride solution needs to be highly concentrated (Fig. 9).

As another example, when Larry and I first tried the procedure, we found that the bottom of the "glass capsule" that Faraday coated with gold chloride solution had to be exceptionally clean or the fluid would

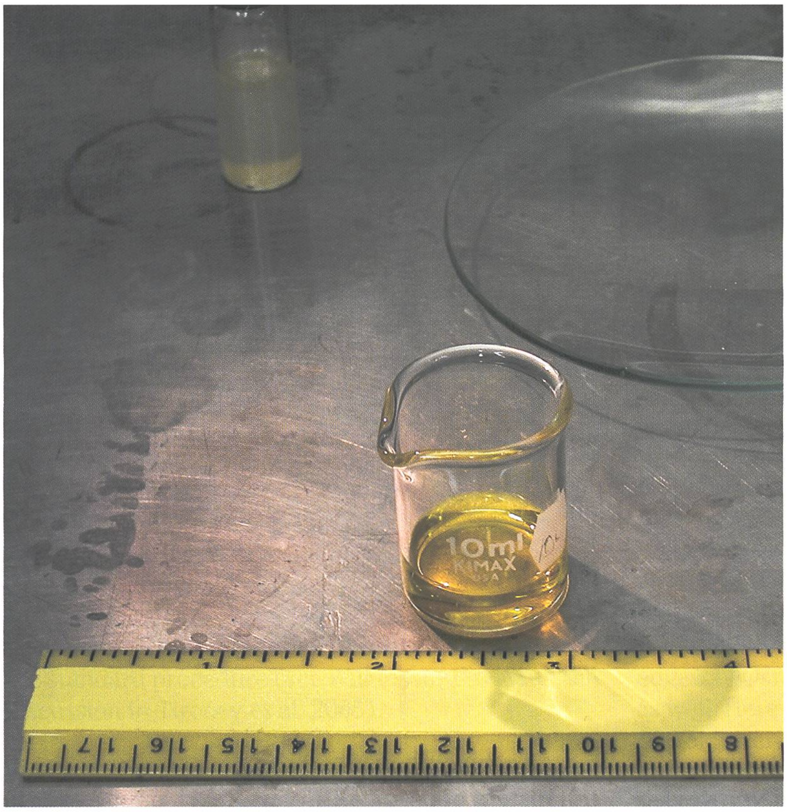


Fig. 9. *A Canadian gold coin, dissolved in Aqua Regia.*

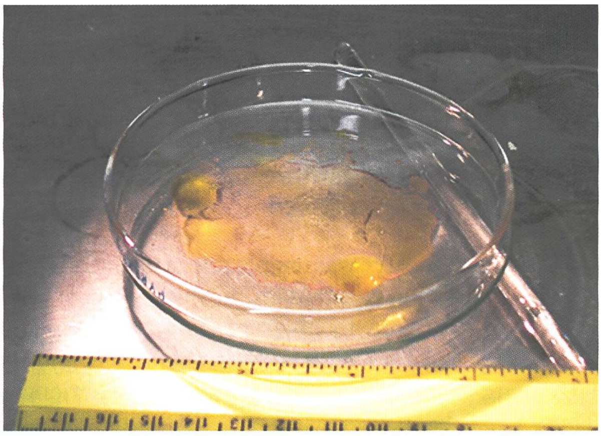


Fig. 10. *Traces of gold film just forming on the bottom of the Petri dish.*

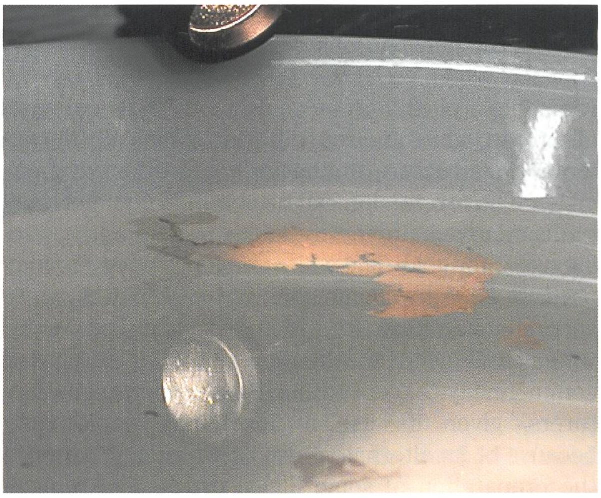


Fig. 11. *A gold film floating on water.*

not adhere evenly. A little rinse in a KOH solution did the trick (I had not thought to use a concentrated base for this purpose). Most importantly, there was quite a bit I needed to know about the safe handling and disposal of the phosphorus and the carbon disulfide, and I was able to learn how to do this under his tutelage.

After preparing several gold films in Larry's lab at Hopkins, I was able to successfully (and safely!) carry out the procedure back home in Bowling Green, and to photograph both the procedure and the results. And in the process, we learned yet more about what Faraday had seen and done.

Faraday's procedure contains one aspect that was, at first, hard to comprehend. He speaks of dissolving phosphorous in sulphuret of carbon, spreading a little of the solution on a "capsule" (we used a common watch glass for this, and a flat-bottomed Petri dish for the gold chloride; see Fig. 10) and letting the sulphuret evaporate. The procedure implies that the phosphorous will then be found as a vapor above the surface of the glass, but why then did the phosphorous not ignite in the air?

In fact, it doesn't, although if bits of phosphorous remain on the glass itself, these are prone to ignite if left alone. However, when the dish containing the gold chloride is inverted over the watch glass, this prevents ignition because, apparently, the phosphorous vapor reacts with any residual oxygen leaving mostly just phosphorous vapor, which then is in contact with the gold chloride. The film formation proceeds for up to about 15 minutes, after which enough film is made to prevent further contact between the chloride solution and the vapor. When the Petri dish is taken away, inverted, and slipped into water (as Faraday described), the very thin and very fragile films will float off onto the surface of the water (Fig. 11).

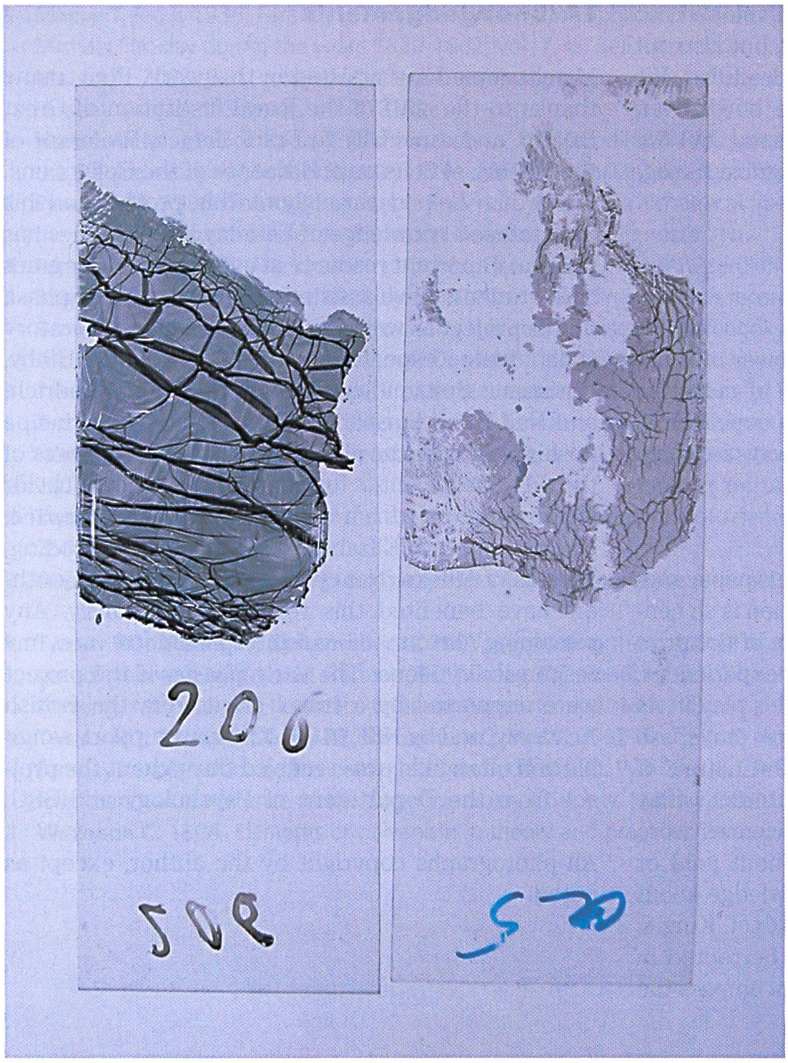
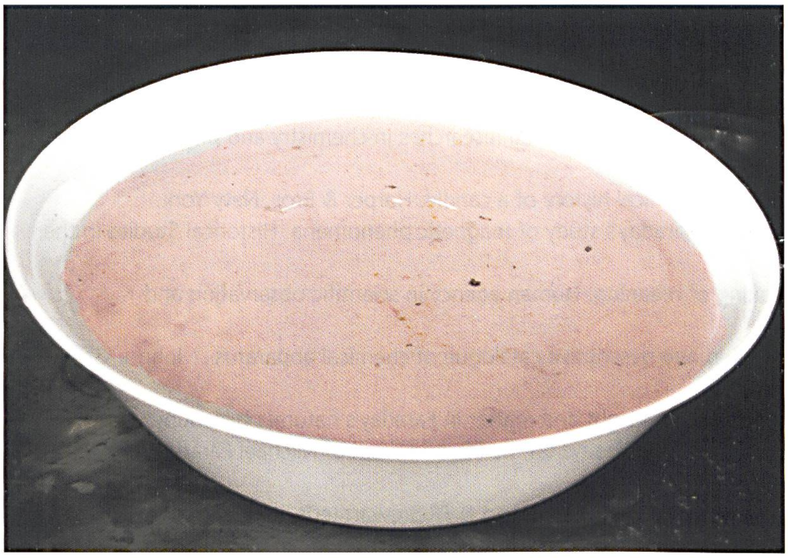


Fig. 12. Faraday's film (left, No. 206, courtesy of the Royal Institution) and one of our films (right).

Fig. 13. Our "Ruby fluid."



Just as Faraday did, we lifted these off onto microscope slides. It's generally necessary to hold one's breathe doing this, since the films are quickly ruined by even the slightest movement of air! When dried, these films closely resembled many of the ones Faraday had prepared (Fig. 12).

Discovering colloids

Chance can affect even the most carefully planned replications. In preparing to photograph our results, I had to fiddle quite a bit with the images of the floating gold film (above, Fig. 11). The films were very thin and the best way turned out to be a reflection off the surface of the film. In the process of this fiddling, I also experimented with different backgrounds. For safety reasons, we were restricted to working inside a fume hood, but we could certainly vary the reaction vessel. And, upon trying a white bowl, my assistant Ryan Mears, recognized something. After making a variety of such films, the water in the white bowl that we had used to lift the gold films had a faint tinge of color that Faraday also had noticed; "a very fine ruby fluid" (Figure 13). As had Faraday, we found that passing a beam of light through some of this fluid produced the scattering typical of a colloid (as in Fig. 4, above). And, like Faraday, we found that the fluid remained a colloid but darkened to a bluish-grey color over the next few days. We had succeeded in replicating Faraday's discovery of metallic gold colloids.

Today, we would be more likely to call our fluid "pink" instead of "ruby," but there is latitude in the color terms, and the more important point is that **this** recognition is in fact "the" discovery of gold colloids. Why Faraday noticed it at this point, what he did subsequently, and how this helps to understand the discovery process in general is a tale told in another place (Tweney 2006). As for our experiences with replication, however, this recognition on Ryan

Mears's part is in fact a central one; it developed out of our close reading of Faraday's **Diary**, but also out of our hands-on familiarity with the procedures. We were lucky to have chosen the white bowl, even though we had done so for other reasons, but we were in fact properly prepared to recognize its significance for the larger story.

Conclusions

The papers in this issue speak to the power of replication as a tool in the understanding of scientific thought in historical contexts. Our own experiences confirm the point and suggest also the ways in which such tools can enliven and deepen the larger project of historical understanding.

The Faraday quote at the beginning of this paper suggested some of the reasons why replication is so central to understanding. Just as knowledge of the principles of science grows out of hands-on experiences, as Faraday noted, and just as it resembles play in its iterative character and its reliance upon "toys," so also does historical understanding of the nature of scientific thinking arise out of the historian's play with the toys of science. Our lab experiences were not directed toward new knowledge about gold or about light, but rather toward new knowledge about the mind and thought of a great scientist (cf. Kurz & Hertwig, 2001). Such knowledge must be rooted in the practices of that scientist if it is to encompass the process by which science is done.

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References

- **Cavicchi E.** 1997. Experimenting with magnetism: Ways of learning of Joann and Faraday. American Journal of Physics, 65: 867-882.
- **Faraday M.** 1827. Chemical manipulation: Being instructions to students in chemistry, on the methods of performing experiments of demonstration or of research, with accuracy and success. W. Phillips, London.
- **Faraday M.** 1857. Experimental relations of gold (and other metals) to light, Philosophical Transactions, 145-181 (read Feb. 5, 1857). Reprinted in M Faraday (ed.) 1859, Experimental researches in chemistry and physics. Richard Taylor & William Francis, London, pp. 391-442.
- **Faraday M.** 1861. A course of six lectures on the chemical history of a candle. Harper & Bros, New York.
- **Gooding DC**. 1981. Final steps to the field theory: Faraday's study of magnetic phenomena. Historical Studies in the Physical Sciences, 11: 231-275.
- **Gooding, DC.** 1990. Experiment and the making of meaning: Human agency in scientific observation and experiment. Kluwer Academic, Dordrecht.
- **Griffin JJ.** 1866. Chemical handicraft: A classified and descriptive catalogue of chemical apparatus …John J. Griffin & Sons, London.
- **James FAJL.** 1985. "The optical mode of investigation": Light and matter in Faraday's natural philosophy. *In*: D Gooding & FAJL James (eds.), Faraday rediscovered: Essays on the life and work of Michael Faraday, 1791-1867. UK: Macmillan, Basingstoke, pp. 137-162.
- **Kurz EM, Hertwig R.** 2001. To know an experimenter. *In:* KR Hammond & TR Stewart (eds.), The essential Brunswik: Beginnings, explications, applications. Oxford University Press, New York, pp. 180-186.

- **Martin T.** (ed.). 1936, Faraday's Diary: Being the various philosophical notes of experimental investigation made by Michael Faraday during the years 1820-1862, vol. 7, G. Bell, London.
- **Mills AA.** 2003. Early voltaic batteries: An evaluation in modern units and application to the work of Davy and Faraday. Annals of Science, 60: 373–398.
- **Nersessian NJ.** 1985. Faraday's field concept. *In*: DC. Gooding & FAJL James (eds.), Faraday rediscovered: Essays on the life and work of Michael Faraday, 1791-1867. Macmillan, Basingstoke (UK), pp. 175-188.
- **Principe LM.** 1998. The aspiring adept: Robert Boyle and his alchemical quest. Including Boyle's "lost" Dialogue on the transmutation of elements. Princeton University Press, Princeton NJ.
- **Puddephatt RJ.** 1978. The chemistry of gold. Elsevier Scientific, Amsterdam.
- **Steinle F.** 2003. The practice of studying practice: Analyzing research records of Ampère and Faraday. *In*: FL Holmes, J Renn, & H-J Rheinberger (eds.), Reworking the bench: Research notebooks in the history of science. (Published as Archimedes, Vol. 7). Kluwer Academic, Dordrecht, pp. 93-118.
- **Taylor C.** 1988. The art and science of lecture demonstration. Institute of Physics Publishing, Bristol.
- **Tweney RD.** 2002. Epistemic artifacts: Michael Faraday's search for the optical effects of gold. *In*: L Magnani & NJ Nersessian (eds.), Model-based reasoning: Science, technology, values. Kluwer Academic (Plenum), New York, pp. 287-304.
- **Tweney RD.** 2004. Replication and the experimental ethnography of science. Journal of Cognition & Culture, 4: 731-758.
- **Tweney RD.** 2006. Discovering discovery: How Faraday found the first metallic colloid. Perspectives on Science, 14: 97-121.
- **Tweney RD, Mears RP, Spitzmüller C.** 2005. Replicating the practices of discovery: Michael Faraday and the interaction of gold and light. *In*: M Gorman, RD Tweney, DC Gooding, & A Kincannon (eds.) Scientific and technological thinking. Mahwah, NJ: Lawrence Erlbaum Associates, pp. 137-158.
- **Tweney RD, Mears RP, Gibby RE, Spitzmüller C, Sun Y.** 2002. Precipitate replications: The cognitive analysis of Michael Faraday's exploration of gold precipitates and colloids. *In*: WD Gray & CD Schunn (eds.), Proceedings of the twenty fourth annual conference of the Cognitive Science Society. Mahwah, NJ: Lawrence Erlbaum Associates, pp. 890-895.
- **Wilkinson C.** 1804. Elements of galvanism in theory and practice, (2 volumes). John Murray, London.