Getting Real: The Hypothesis of Organic Fossil Origins

P. Kyle Stanford

Department of Logic and Philosophy of Science

University of California, Irvine

1. Scientific Realism and Unconceived Alternatives

Scientists and philosophers of science alike have long worried about whether and how our belief in even the best contemporary scientific theories should be tempered or mitigated by our awareness that the evidence we have in support of those theories might also strongly support alternative hypotheses that we have failed to consider. As Mill wrote in *A System of Logic*,

> Most thinkers of any degree of sobriety allow, that an hypothesis . . . is not to be received as probably true because it accounts for all the known phenomena, since this is a condition sometimes fulfilled tolerably well by two conflicting hypotheses . . . while there are probably a thousand more which are equally possible, but which, for want of anything analogous in our experience, our minds are unfitted to conceive.[1]

Although Mill here worries about hypotheses that we are *incapable* of conceiving, an apparently more tractable obstacle to belief in contemporary theories is posed by the possibility of theoretical alternatives that we could but simply have not yet managed to conceive. As Pierre Duhem memorably expressed this challenge,

> Do two hypotheses in physics ever constitute . . . a strict dilemma? Shall we ever dare to assert that no other hypothesis is imaginable? Light may be a swarm of

projectiles, or it may be a vibratory motion whose waves are propagated in a medium; is it forbidden to be anything else at all?[2]

Concerns about the general worry articulated here also seem to have become especially acute in more recent philosophy of science, for example in the work of such luminaries as Abner Shimony[3], Larry Sklar[4], and John Earman[5], but none of these more recent discussions have offered any convincing reason to think that the challenge is not a serious one. Most recently, I myself have suggested[6] that the historical record of scientific inquiry itself provides convincing inductive grounds for believing that the existence of such unconceived but nevertheless well-confirmed theoretical alternatives is not simply a speculative possibility but most likely represents our actual epistemic predicament in theoretical science. And I suggested that this 'problem of unconceived alternatives' constitutes a quite general challenge to our justification for believing in the truth of what I described (for lack of a better term) as our 'fundamental' scientific theories.

Even in that earlier work, however, I made a point of emphasizing that the problem does not pose a serious challenge to all scientific beliefs whatsoever. I suggested that the scope of Duhem's challenge was limited to beliefs whose central evidential support was eliminative or abductive in character—that is, beliefs accepted primarily because they offer the best or only known explanation for a given body of evidence (typically following the convincing elimination of other possible explanations)—and that many scientific claims simply do not depend (or at least do not depend primarily) on this sort of eliminative or abductive evidential support.[7] I suggested, for example, that our beliefs that pure sodium will burst into flame when placed in water, that dinosaurs roamed the Earth long ago, and that tiny creatures invisible to the naked eye fill the world around us are not supported primarily in an eliminative or abductive manner, and that our justification for believing these claims is therefore not seriously threatened by the possibility of unconceived theoretical alternatives. The ability of microscopes (and systems of combined lenses more generally) to render objects or features of objects easily visible whose minuteness makes them difficult but not impossible to see otherwise, for example, can be demonstrated independently of whether the theoretical hypotheses about light and matter on which their construction depends are true, and it is that demonstration above all which leads us to believe that microscopes reveal organisms invisible to the naked eye. Although outlandish alternative explanations for our microscopic observations (or for fossils of the dinosaurs, or for sodium explosions) could be and sometimes are *imagined*, it is not by ruling out the possibilities that fossils are a test of our faith from God or that beyond a certain level of resolution microscopes mysteriously introduce amoeba-like perceptual artifacts that we come to have justification for (or actually come to believe) these claims.[8]

In the present paper I will take up a closely connected example in considerably greater detail, in order to more fully explore the sorts of considerations that make a difference to the significance of the epistemic threat posed to a given scientific belief by the problem of unconceived alternatives. The example I will consider is what I will call the “hypothesis of organic fossil origins”: the belief that the fossils we find in nature are the remains of once-living organisms. This is a particularly illuminating case, I suggest, because in it the seriousness of the challenge posed by the problem of unconceived alternatives to our justification for believing *one and the same* scientific claim has undergone a significant change: although the hypothesis of organic fossil origins was once eminently vulnerable to the epistemic challenge posed by this problem, I suggest that it is now far less vulnerable to any serious version of that challenge. I will argue, however, that this shift is not simply the result of accumulating more and more evidence in support of the hypothesis but also, and more importantly, a change in the fundamental form of the central evidence providing that confirmation. More specifically, the vulnerability of the hypothesis of organic fossil origins to any serious version of the challenge posed by the problem of unconceived alternatives has been most dramatically reduced by the fact that we have managed to supplement the fundamentally abductive sorts of evidence long available in support of it with compelling further evidence that depends instead on a more straightforward sort of inductive projection. Although this is far from an exhaustive answer to questions about whether, when, or how much the problem of unconceived alternatives poses a serious epistemic challenge to a given scientific claim or theory, this example does at least suggest that the most critical element in that determination will not be the sort of entities the belief is about, what properties they have, who holds it, how long it has survived, what area of science it comes from, or what form the belief takes, but instead *what kind(s) of evidence we have in support of it*.

2. An Historical Interlude

We must begin by divesting ourselves of the crudely Whiggish idea that the organic origin of fossils was somehow immediately obvious or incontrovertible, at least for reasonable people whose minds were not clouded with superstition or religious dogma. Even by the dawn of modern geology in the Renaissance it was by no means an established scientific conclusion that fossils have an organic origin: when Conrad

Gessner completed *On Fossil Objects* in 1565, "fossil" was simply a generic term for any object extracted from the earth or found on its surface, while the idea that those 'fossils' bearing striking resemblances to living creatures were organic in origin was just one hypothesis among several alternative theoretical possibilities and not even the leading or most promising candidate.

For one thing, substantial empirical challenges faced any general hypothesis of organic origin for fossils resembling plants and animals. Prominent among these challenges was the problem posed by the locations in which such fossils were found. Marine fossils were routinely discovered, for example, on the tops of hills and high in mountains far from the sea. While silting and earthquakes had been known to displace land and sea by several miles, the hypothesis of organic origin therefore seemed to require geological change on a scale almost preposterously outstripping any convincing available evidence. Moreover, there was the simple problem of the position of such fossils *inside* rocks bearing little obvious resemblance or relation to loose sediments: if these were organic remains, how did the original organisms get inside?

Even more important than these empirical challenges of location and position for the hypothesis of organic fossil origins, however, was the fact that existing alternative hypotheses seemed to offer more convincing explanations of the distinctive *pattern* of resemblances in form between fossils resembling plants or animals and living organisms. As Martin Rudwick documents in detail in his classic and still-authoritative study[9] (on which I rely heavily throughout this section), neither of the dominant scientific theoretical traditions of the 16th Century embraced the hypothesis of organic fossil origins, and each offered an alternative account widely regarded as better supported by the evidence.

The early modern study of 'fossils' took place against the backdrop of Renaissance Neoplatonism, which saw the world as including a vast "network of hidden affinities and 'correspondences', which might be made manifest by resemblances not only between microcosm and macrocosm, but also between the heavens and the Earth, between animals and plants, and between living and non-living entities."[10] The ability of such affinities and resemblances to act at a distance seemed to provide rationally satisfying explanations for phenomena like the attractive powers of lodestones and pieces of amber, while similar sorts of sympathies and antipathies were invoked to explain such phenomena as the medicinal values of specific plants and the supposed powers and protections offered by non-organic 'fossils' like gemstones. According to the influential amalgam of such Neoplatonism with the writings of Hermes Trismegistus (mistakenly believed at the time to be both an ancient Egyptian priest who lived in the time of Moses and the source of Plato's wisdom), the idea that some objects made of stone and buried in the earth would bear close and detailed resemblances to living organisms was simply another manifestation of this hidden network of correspondences, analogies, and affinities that linked all the diverse parts of nature into a coherent and intelligible whole.

Such Hermetic Neoplatonists certainly wondered about the stony character of their 'fossils', and they sought to understand the detailed workings of what was believed to be a more general petrifying agency responsible for the growth of stalactites, corals, the supposed replenishment of mined ores and minerals, and the like.[11] But the causal origin of the *shapes* or *forms* of fossils resembling organisms seemed a distinct problem whose solution could be attributed to the operation within the Earth of the very same 'moulding force' or *vis plastica* they held to direct the growth and development of living organisms themselves. The central problem for these thinkers was not why some stones were formed in the shapes of plants and animals or their parts, but why stones should be found in distinctive shapes resembling a wide and heterogeneous array of other entities *at all*. Indeed, thinkers of this period were so far from seeing the problem as one of distinguishing 'fossils' of organic from inorganic origin that they simply classified 'fossil' objects quite *generally* by their resemblances to various natural and even artificial forms: from geometrical figures and Aristotelian elements to heavenly bodies and other atmospheric phenomena as well as to terrestrial objects, including 'fossils' resembling the products of human artifice or workmanship in addition to those resembling a wide variety of plants and animals.[12]

Perhaps ironically, it was often the *inadequacy* of these resemblances that prevented the hypothesis of organic origins from being especially convincing. It is easy to forget that theorists have not been continuously presented with fossils as they are processed, arrayed, and (perhaps most importantly) *selected for display* in modern museums, and of course the deformations and other alterations introduced by the various processes of fossilization made such correspondences both imperfect and harder to recognize. But far more importantly, the *unfamiliarity* of many of the organisms whose fossil remains were being discovered made it seem much more as if it were simply animal-*like* and plant-*like* shapes that had somehow formed in the rock. In the opposite direction, the purely fortuitous resemblances of some fossils to organic forms that had clearly *not* produced them (such as that of a stony concretion to a human finger or foot) made any easy inference from fossil shape to organic origin immediately dubious. It is not hard to see how Hermetic Neoplatonists could have regarded the idea that fossils shaped like plants and animals were actual remains of once-living organisms as a charming vestige of an inadequate knowledge of the detailed characteristics of 'fossil' objects, and regarded the hypothesis that fossil resemblances to living plants and animals are a manifestation of the quite general hidden network of affinities and correspondences intertwined throughout the natural world as a far more informed, sophisticated, and credible successor.

Alternatives to the hypothesis of organic origins were not limited to Hermetic Neoplatonism, however, for the opposing Aristotelian tradition that would so profoundly influence later biological research offered a distinct account of the resemblances between some 'fossils' and living creatures. Just as simple organisms containing a 'vegetative spirit' (*anima vegetativa*) could be formed by spontaneous generation from non-living materials, neo-Aristotelians supposed that the distinctive forms of living things might develop not only on the Earth's surface or in its seas, but within the Earth itself, forming fossils from the stony materials found there. The shape of more complex organisms might be similarly generated by the form present in their characteristic seeds acting on the materials of the Earth, carried there by such natural processes as the percolation of groundwater. On this neo-Aristotelian account a particular fish-like fossil would owe its shape to essentially the same causal process that produced a living fish operating on the stony matter of the earth itself, rather than representing the organic remains of anything at all.[13] Thus, while the hypothesis of organic origin was always a candidate explanation for the resemblance of at least some fossil objects to organisms, particularly for the very 'easiest' cases of marine mollusk shells of relatively recent origin lying in unconsolidated sediments near the sea, it was by no means obviously correct, best supported by the weight of the available evidence, or even the foremost contender among the various theoretical possibilities:

> Even when resemblances between fossils and living organisms could be clearly perceived, it did not seem to follow necessarily that the fossils were actually the remains of living organisms. This inference, so obvious to us today, was not avoided in the sixteenth century for reasons of intellectual conservatism or out of any sense of conflict with religious orthodoxy. It was usually ignored or rejected on the far more positive grounds that…[b]oth the renewed Aristotelianism and the synthetic Neoplatonism of the sixteenth century…provided the phenomenon of organic resemblance with explanations that were quite as persuasive, indeed more so, than the hypothesis of organic origin. Aristotelians could attribute organic resemblances to the growth *in situ* of objects combining the form of genuine organisms with the stony matter appropriate to all 'fossils'; objects for which the causal explanation lay in spontaneous generation or the implantation of specific 'seeds' within the Earth. Neoplatonists could attribute the same resemblances to the action of a pervasive moulding force or 'plastic virtue', which made visible the hidden web of affinities that bound all parts of the cosmos into one. In either case, the explanations successfully accounted for the fact that the resemblances varied from the striking to the barely perceptible, and they

> were therefore more widely applicable and more 'successful' than the hypothesis of organic origin.[14]

Against this background it is perhaps unsurprising that the question of fossil origins would remain a matter of heated scientific controversy after more than a hundred years of further sustained investigation. In the mid-17th Century, defenders of the hypothesis of organic origin like Steno and Hooke were first obliged to confront the still widely accepted view that fossils owed (in Hooke's words) "their formation and figuration" to some "kind of *Plastick virtue* inherent in the earth" or had otherwise originally formed inside the rocks in which they were found.[15] Although Steno's essay on the *glossopetrae* or 'tongue-stones' containing fossil shark's teeth ('easy' cases for which the empirical challenges of form and location were weakest) defended the hypothesis of organic origin, even here he limited himself to making the positive case, explicitly leaving the negative case to others and disclaiming any right to certainty in the matter. Hooke's argument appealed to the detailed functional resemblances between fossils and living organisms, but both thinkers had to face the same fundamental problems concerning the location, position, and exact forms of fossils with which their predecessors had struggled: Steno followed many earlier writers in attributing the present locations of fossils to the action of the Great Noachian Deluge recorded in the Bible, while Hooke rejected this explanation as inadequate in his later writings and argued instead that this had been accomplished by violent earthquakes acting on a more hot and fluid early Earth, creating mountains from land that had previously been under the seas.[16]

Meanwhile, serious resistance to the hypothesis of organic origin remained alive and well among many influential and informed members of the relevant scientific community. The English naturalist Martin Lister was perhaps better positioned than any scientist of his day to appreciate just how detailed and striking the similarities between many common fossils and some living organisms really were, but he nonetheless argued emphatically against any general hypothesis of organic origin: although he was willing to accept an organic interpretation for Steno's 'easy' Italian fossils, he nonetheless insisted that the English fossils with which he himself had the greatest familiarity simply could not be the preserved remains of once-living organisms. For one thing, he insisted, "there is no such thing as *shell* in these resemblances of shells."[17] Furthermore, if the shells that would become fossils had simply been thrown up onto the land (as Hooke had earlier suggested), their distribution should not exhibit such dramatic local variation between different points of discovery and different types of rock: the fact that particular types of shells were characteristic of particular strata suggested instead that they had grown or formed there originally, just as different plants grew in different characteristic habitats across the surface of the Earth. But finally and most importantly, Lister pointed out that fossil shells resembled living species only in general and not in their more specific details. Unlike Steno's specimens, he noted, "our English Quarry-shells…were not cast in any *Animal Mold,* whose species or race is yet to be found in being at this day." He sharply criticized those who were content with such crude similarities as insufficiently attentive to "heedful and accurate descriptions", and insisted that until living mollusks were discovered that were genuinely identical with fossil specimens he would continue to believe that "there is no such matter, as Petrifying of Shells in the business…but that these Cockle-shells ever were, as they are at present, *lapides sui generis*, and never any part of an Animal."

Careful attention to the details of the fossil record thus seemed to pull in opposite directions: the level of functional detail preserved in many fossil specimens made their organic origin seem more plausible, but the differences in these details between most fossils and living organisms made it seem radically less so. Moreover, as increasing numbers of fossils corresponding to no known living species were uncovered and systematically catalogued, as well as ever more marine specimens in locations ranging as far from the sea as the Alps, the challenges of form and position became increasingly acute and the debate shifted from the 'easy' Italian cases to far more problematic specimens found elsewhere. Thus, as the beginning of the 18th Century approached it could fairly be claimed that the hypothesis of organic fossil origins was becoming harder and harder to defend as more and more empirical evidence accumulated.

Lister's objections weighed heavily with John Ray, arguably the greatest naturalist of the age, who laid out the arguments both for and against organic origin with characteristic fairness, citing Hooke and Lister as their respective champions. Although his ultimate conclusion was that the detailed functional correspondences between fossils and living organisms made the organic origin of fossils the most probable opinion, he continued to be deeply troubled by problems both about the locations in which fossil specimens were found (for which he could accept neither Steno's Flood nor Hooke's earthquakes as an adequate explanation) and the lack of precise correspondence between fossil and living species.[18] Because he could not accept extinction, the only solution Ray could see to the problem of form was to assume that the living forms of many fossilized species simply had not yet been discovered. And indeed, the living form of the very stalked crinoid fossils for which Ray originally advanced this suggestion would be discovered only a half-century after his own death. But he was unwilling to embrace this solution in a fully general way in any case: despite his own early conviction that ascribing an organic origin to some fossils resembling organisms and not others was "but a shift and a refuge to avoid trouble", Ray found himself increasingly pushed towards this uncomfortable resolution.[19] In a later essay he singled out ammonites as the most puzzling fossils of all: Ray felt that Hooke had offered convincing reasons for believing in an organic origin for ammonite fossils, but he could not accept the existence of a well-populated *genus* from which not even a single living species had been discovered, and therefore reluctantly relegated ammonites to the inorganic side of the divide.[20]

Perhaps it is unsurprising, then, that Ray ultimately found himself attracted as well to the theory of his friend and distinguished fellow naturalist Edward Lhwyd, who was, like Lister, a knowledgeable collector of fossil specimens. By this time studies of spermatozoa and pollen under the microscope had provided substantial support for 'animalculist' theories of the generation of organisms that treated organismic characteristics as embodied in the seed of a species, and Lhwyd pointed out that fossils with the most detailed resemblances to living forms seemed to correspond to organisms with external fertilization. Thus, at the turn of the 18th Century Lhwyd echoed earlier neo-Aristotelian explanations of fossil remains by once again proposing that most fossils had grown *in situ* from the very same 'seeds' that produced the living descendants they resembled when those seeds found entry through crevices and by other means of infiltration into the rocks.[21] Ray found this proposal attractive, but he remained undecided through the end of his life as to the correct account of fossil origins and the correct explanation of the resemblances between fossils and living organisms and the matter would remain controversial well into the 18th Century.

3. Taphonomy and Projective Evidence

This survey of part of the history of our theorizing about fossil objects has of necessity been fairly superficial, but my hope is that it nonetheless serves to make the central point that for at least the better part of two centuries of that history in the modern era, the evidence available for and against the hypothesis of organic fossil origins was fundamentally, perhaps even exclusively, abductive in character. The battleground for competing theories of fossil origins throughout this period really was the comparative ability of those theories to *explain* such phenomena as the level of functional detail exhibited by fossil objects and their resemblances to living organisms, the locations in which such fossils were found, and the residual differences in morphology between them and extant organisms. Those who accepted the hypothesis of organic fossil origins in this period did so because they saw it as providing the best explanation for a number of otherwise puzzling characteristics of many fossils, most importantly, their striking similarities of form to extant organisms. And those who rejected it did so because they felt that important features of the available evidence were not explained by the hypothesis of organic fossil origins and/or that some alternative account of fossil origins offered a more convincing explanation of that evidence taken as a whole.

It also seems hard to resist the suggestion that throughout the period under discussion the hypothesis of organic fossil origins remained eminently vulnerable to the threat posed by the problem of *unconceived* alternatives: it would have been perfectly reasonable for an impartial, fully informed thinker like Ray, for example, to believe not only that well-confirmed alternative theoretical accounts of fossil origins remained unconceived by himself and his contemporaries, but also that the correct account might well be among them. But I now want to suggest that the hypothesis of organic fossil origins no longer remains vulnerable to that challenge and is *now* a belief that only a radical or hysterical skepticism could prevent us from endorsing as at least probably and/or approximately true. I also want to suggest, however, that this change in epistemic status has *not* been produced simply by the accumulation of more and more evidence in support of the hypothesis of organic origin, but instead by a fundamental change in the character of the evidential support for that hypothesis. More specifically, I suggest that this shift in the epistemic status of the hypothesis of organic fossil origins is itself a consequence of the fact that we have managed to *supplement* the distinctively abductive sorts of evidence available in support of it throughout the early centuries of the modern era with compelling further evidence that depends instead upon a more straightforward kind of inductive projection.

The most significant change in our evidence from the time of Lister, Ray, and Lhwyd to the present day is the accelerating depth and breadth of our knowledge of what is sometimes called actuopaleontology or taphonomy, described by J. A. Efremov who coined the latter term in the 1940's as "the study of the transition (in all its details) of animal remains from the biosphere into the lithospere."[22] Taphonomic research gives us detailed experimental and direct observational evidence of the processes that act at each stage of fossilization to produce the fossils we encounter from the remains of organisms—that is, of how specific parts of deceased organisms are selected and transformed by processes of disarticulation, scavenging, trampling, decay, weathering, hydraulic transport, mineralization, and diagenesis to produce fossil remains like those we discover in excavated natural surroundings. Collectively, these processes simply *constitute* "the transition in all its details of animal remains [and those of other organisms] from the biosphere into the lithosphere", albeit combined sequentially and sometimes operating over longer time scales than we are able to observe directly. Indeed, the following passage from an introductory textbook in the field emphasizes that contemporary taphonomists explicitly conceive of their knowledge of fossilization in past environments as projected inductively in just this way from their study of the ongoing processes they investigate in the lab and in the field:

> To decipher the physical evidence left by different taphonomic events, researchers must rely heavily on studies of what happens to modern bone assemblages in natural environments. Binford and Bertram (1977), Gifford (1977), Hill (1976, 1978), Behrensmeyer and Dechant-Boaz (1980), Shipman (1975), Shipman and Phillips-Conroy (1977), Payne (1965), Brain (1967, 1980), Sutcliffe (1970), Crader (1974), Haynes (1980), and Yellen (1977) are among those who have done such studies. Because of their work, it is increasingly possible to link the visible characteristics of fossils with particular events and even, in some instances, estimate the duration of the events. Work using the scanning electron microscope (Shipman, 1981) has yielded a more precise definition of the changes produced in bones and teeth by different taphonomic events (see Chapter 8).[23]

Notice that in this description the operation of various taphonomic processes in the past is not *hypothesized* to account for a set of phenomena or body of evidence, but instead *projected* from what actually happens to organic remains in the field and in the laboratory.[24] The structure of this inference is further clarified by many of the detailed reports of classic taphonomic investigations offered in the same introductory textbook:

> Binford and Bertram (1977) examined the differential survival of sheep bones exposed to scavenging by dogs. They found a distinct correlation among the density of the portion of each bone, the age of the animal, and the probability of survival of each portion of bone. They observed that for species that gave birth seasonally, a graph of the density of parts of skeletal elements would show discrete clusters of data representing age classes. These data provide a useful analysis of the differential survival of skeletal elements exposed to medium-sized scavengers.[25]

> Shotwell (1955, 1958) was among the first to suggest that the representation of different taxa in a fossil assemblage is often a function of hydrodynamic transport…. Those who have built upon his theory with experimental work have emphasized the importance of three factors Shotwell ignored: the size, density, and shape (SA/V ratio) of the individual bones.[26]

Voorhies (1969), Behrensmeyer (1975), Boaz and Behrensmeyer (1976) and Korth (1979) have focused on the hydrodynamic transport of bones in artificial streams or flumes. After observing the behavior of bones of medium-sized animals (sheep, coyote) in a flume, Voorhies defined three groups of skeletal elements according to their potential for hydraulic dispersal (Table 2.1). The Voorhies Groups show which skeletal elements are likely to be deposited and transported together by hydraulic forces, and they can be used to deduce the degree of transportation and sorting that has occurred during the formation of a fossil assemblage.[27]

The way each type of bone fragments, weathers, and breaks when chewed is predictable…. Evans (1973) summarized the extensive literature on the various experiments that have been performed to determine the mechanical properties of different bones when subjected to tension, compression, shear, and torsion. In many instances, the different mechanical properties of two types of bones—say, a femur and a fibula—can be directly related to aspects of their microscopic structure, such as the density of canals for blood vessels or the proportion of newly deposited and poorly mineralized bone. Further support comes from Shipman's (1977) observation of a statistically significant relationship between the shapes of broken bone fragments and the skeletal elements from which they are derived. Similarly, Tappen (1976) demonstrated that cracks and splits produced by natural weathering reveal the bone's basic structural patterns (see also Lakes and Saha, 1979). In addition, how the bone was broken and its condition at the time influence the shapes of the resulting fragments (Sadek-Kooros, 1972; Bonnichsen, 1979); see Chapter 7 on breakage.[28]

Fossils or bones in sediments may undergo several types of change during diagenesis. Minerals may be precipitated in the voids of the skeletal remains left by the decay of organic minerals. This process, called impregnation or permineralization, may result in the preservation of exceptionally fine details in fossils. The microscopic structure of bones or teeth may be clearly preserved despite the obvious fragility of such small structures. Horizons containing many skeletal elements may be more permeable, which leads to unusually rapid permineralization (Rolfe and Brett, 1969). The original mineral matrix of bones and teeth may also be replaced by other minerals. It now seems unlikely that such replacement occurs in the molecule-by-molecule method that was once widely accepted (Rolfe and Brett, 1969), although as in impregnation, fine structures may be preserved.[29]

Another source of postfossilization bias occurs when a fossil is eroded out of its matrix. Unless the fossil is collected shortly after exposure by erosion, it may fragment or become reworked in a second depositional environment. The rate at which a fossil breaks up after exposure is a

> function of the degree of replacement or permineralization that has occurred and of the natural forces to which the fossil is exposed.[30]

It is important to emphasize that taphonomic inquiry is not limited to field observations of organic remains in various stages of the process of fossilization. Experimental taphonomists also recreate in the laboratory the conditions under which taphonomic processes occur in nature to examine the outcomes of those processes under particular circumstances: *we can and do make fossils*. The following abstract is from a classic paper in this tradition of experimental taphonomy entitled "Artificial Microfossils: Experimental Studies of Permineralization of Blue-Green Algae in Silica":

> A technique has been developed to artificially fossilize microscopic algae in crystalline silica under conditions of moderately elevated temperature and pressure. The technique is designed to simulate geochemical processes thought to have resulted in the preservation of organic microfossils in Precambrian bedded cherts. In degree of preservation and mineralogic setting, the artificially permineralizaed microorganisms are comparable to naturally occurring fossil algae.[31]

Of course, in contemporary investigations the goal is not to test the hypothesis that fossils *generally* are the remains of once-living organisms, as this is a settled question for modern taphonomy. Instead, today's taphonomists typically investigate whether particular types or categories of organic remains can be mineralized, how those remains are affected by this and other taphonomic processes, and/or the conditions under which such processes will or will not occur. In "Experimental Mineralization of Invertebrate Eggs and the Preservation of Neoproterozoic Embryos", for example, the authors report their success in fossilizing invertebrate eggs even with no decaying carcass to serve as an external source of phosphorus or calcium:

> Here we show that rapid mineralization of invertebrate eggs is possible under laboratory conditions. Under anaerobic conditions, eggs become coated in mainly calcium carbonate within three weeks. Preservation of the external morphology is comparable to that of fossil material, but no internal mineralization was observed in the laboratory. This is the first report of laboratory mineralization of metazoan eggs in the absence of a decaying carcass, and demonstrates that eggs, and probably small embryos, can be preserved in the absence of larger organisms as a source of phosphorus or calcium. Thus, it is possible for organisms of this size to have been fossilized prior to the evolution of large metazoans.[32]

Similarly, "Fossilization of Soft Tissue in the Laboratory" reports the mineralization of modern shrimps without any external source of calcium phosphate:

> Some of the most remarkable fossils preserve cellular details of soft tissues. In many of these, the tissues have been replaced by calcium phosphate. This process has been assumed to require elevated concentrations of phosphate in sediment pore waters. In decay experiments modern shrimps became partially mineralized in amorphous calcium phosphate, preserving cellular details of muscle tissue, particularly in a system closed to oxygen. The source for the formation of calcium phosphate was the shrimp itself. Mineralization, which was accompanied by a drop in pH, commenced within 2 weeks and increased

> in extent for at least 4 to 8 weeks. This mechanism halts the normal loss of detail of soft-tissue morphology before fossilization. Similar closed conditions would prevail where organisms are rapidly overgrown by microbial mats.[33] (1992 1439)

Perhaps ironically, in modern taphonomic research it is no longer always necessary to actually mineralize particular organic remains in order to demonstrate their suitability for fossilization; instead it is sufficient to show that particular conditions will preserve the detailed structure of those organic remains for what we *already know* to be a long enough period for mineralization to occur. Raff, et. al.'s "Experimental taphonomy shows the feasibility of fossil embryos", for instance, simply explores the length of time for which marine embryos can resist decomposition under various circumstances as a way of investigating the 'preservation potential' of such embryos:

> The recent discovery of apparent fossils of embryos contemporaneous with the earliest animal remains may provide vital insights into the metazoan radiation. However, although the putative fossil remains are similar to modern marine animal embryos or larvae, their simple geometric forms also resemble other organic and inorganic structures. The potential for fossilization of animals at such developmental stages and the taphonomic processes that might affect preservation before mineralization have not been examined. Here, we report experimental taphonomy of marine embryos and larvae similar in size and inferred cleavage mode to presumptive fossil embryos. Under conditions that prevent autolysis, embryos within the fertilization envelope can be

> preserved with good morphology for sufficiently long periods of mineralization to occur. The reported fossil record exhibits size bias, but we show that embryo size is unlikely to be a major factor in preservation. Under some conditions of death, fossilized remains will not accurately reflect the cell structure of the living organism. Although embryos within the fertilization envelope have high preservation potential, primary larvae have negligible preservation potential. Thus the paleo-embryological record may have strong biases on developmental stages preserved. Our data provide a predictive basis for interpreting the fossil record to unravel the evolution of ontogeny in the origin of metazoans.[34]

Intriguingly, the authors here readily acknowledge the ability of the hypothesis that the targets of their investigation are fossil embryos to explain their similarities of form to modern marine animal embryos or larvae, but because those targets also resemble "other organic and inorganic structures" they explicitly reject the idea that this abductive support constitutes a sufficient reason to accept or believe the hypothesis. In place of actually fossilizing the closest modern analogues to the presumptive metazoan sources of the organic remains in question, however, they themselves simply examine the relevance of such conditions as embryo size, presence of a fertilization envelope, and chemical composition of the seawater to the length of time for which modern marine embryos can be preserved, and they treat such preservation as a reasonable proxy for the actual mineralization of the embryos in question. The results of this investigation in turn suggest which present-day objects are and are not plausible candidates for fossilized remains of ancient organisms, what features or objects we might not expect to find represented among fossil remains even if they were abundantly present in past environments, what other biases to expect in the embryological fossil record, and so on.

Again, the point of such taphonomic investigations is not to establish any general hypothesis of organic fossil origins, but instead to determine whether particular objects are indeed fossils and whether particular conditions are among those in which we can expect fossils to be formed. But the evidence they bring to bear on such questions is nonetheless projective rather than abductive in character, and the fact that the extensive abductive evidence in support of the general hypothesis of organic fossil origins has been supplemented with this body of convincing projective evidence also constitutes the best reason we have for accepting that hypothesis. That hypothesis gains abductive support from the fact that it offers the best known explanation of the similarities of form to living organisms and other characteristics of fossils, but it gains projective support from detailed taphonomic demonstrations that organic remains deposited in both natural and laboratory settings *actually become* fossils.

My suggestion, then, is that we have not simply accumulated more and more evidence for the hypothesis of organic fossil origins since the time of Lister, Lhwyd, and Ray, but instead we now have substantial evidence of a distinctive *kind* that these thinkers were lacking almost entirely. We no longer believe that fossils have an organic origin simply because this hypothesis would explain so many things about fossils so well, but also because we have discovered a set of processes continually occurring in nature that sequentially transform specific parts of living organisms into fossil remains like those we encounter in natural settings. Our belief that the fossils we find in nature are the remains of once-living organisms is grounded in a fairly simple inductive projection of those processes from cases in which we have witnessed or put them to work ourselves to cases in which we have not, albeit combined and expanded to a scale on which it would be impossible for us to do so. We might well never have been able to accumulate this detailed experimental and observational knowledge of taphonomic processes without our initial suggestive abduction concerning fossil origins, but this simply doesn't bear on what constitutes the most convincing justification we now have for the hypothesis of organic origins.

I do not mean to suggest, of course, that most people today believe the hypothesis of organic fossil origins on these projective grounds, for most people have never even heard of taphonomy and we are all obliged to accept most of our scientific beliefs on the strength of authoritative testimony in any case. Nor do I mean to suggest that such taphonomic evidence was what ultimately turned the weight of scientific opinion in favor of the hypothesis of organic fossil origins. But the further developments that did ultimately produce a consensus in favor of the hypothesis of organic fossil origins (long before Darwin) offer little reassurance to anyone who imagines that such a consensus forms only in response to evidence that will continue to be regarded as dispositive in perpetuity. The most important such development was the widely influential account offered in Woodward's *Essay Towards a Natural History of the Earth* of the distribution of fossils by a (more flexibly interpreted) Noachian Flood: as a consensus steadily grew in favor of the hypothesis of organic origins, Rudwick notes, "it was the diluvialists whose work most encouraged the acceptance of an organic interpretation of fossils."[35] Moreover, the threat of extinction (and its theological implications) no longer stood firmly in the way of accepting organic fossil origins "not because extinction had become any more acceptable, but because the exploration of the sea in distant parts of the world gave increasing grounds for doubting whether any fossil species were in fact extinct", as illustrated by the eventual discovery of the living stalked crinoids that Ray had hopefully suggested might simply be undiscovered rather than extinct.[36] And of course, one of the central points of *Exceeding Our Grasp* was that scientists and scientific communities have *routinely* accepted beliefs by consensus when alternative theoretical possibilities well confirmed by the available evidence simply remained unconceived, often including alternatives that would ultimately come to replace such earlier consensus views. Thus neither the details of this case nor the historical record more generally suggests that the evidence producing a scientific consensus is automatically or even presumptively a secure basis for theoretical scientific knowledge. This record is also what cautions us most strongly against thinking that the simple fact that the hypothesis of organic fossil origins is now supported by more and better abductive evidence than it was at the turn of the 18th Century (as it surely is) should or would alone be sufficient to deflect the challenge posed by the problem of unconceived alternatives even without the further projective evidence we have considered.

What I do claim is that the projective evidence we have in support of the hypothesis of organic fossil origins is *in fact* the most important consideration rendering that hypothesis far less vulnerable to the problem of unconceived alternatives now than it was in the 16th, 17th, and even 18th Centuries, especially in contrast to the weight of abductive evidence around which a scientific consensus in favor of organic fossil origins ultimately formed. And more generally, the particulars of this case suggest that even a consensus in favor of a given theoretical scientific belief should be regarded with considerably more suspicion when the evidence we have in support of that belief is exclusively or even just centrally abductive in character.

4. Taking Stock: Abductive Evidence, Projective Evidence, and Varieties of Science

It is, of course, always *possible* to reframe the sort of projective justification we have been considering in abductive terms: if we know from wide experience that smoke is typically caused by fires, and we see smoke, we can say either that our belief in the fire that caused it is based on inductive projection from that experience or that, in light of that experience, positing a fire offers the best explanation for the smoke we observe. It is similarly open to us to say that our belief in the organic origins of fossil objects is a result of inductively projecting into the past the operation of processes we have observed and even brought about ourselves in the present day, or instead that the hypothetical postulation of those same processes operating in the distant past is the best explanation of the fossil evidence we now find. Although observing taphonomic processes in nature and making fossils ourselves certainly seems to support the hypothesis of organic fossil origins by satisfying something much more akin to the demand for a *vera causa* so prominent in 19th Century science than by verifying yet another of that hypothesis' empirical implications (viz., that it should or at least might be possible to fossilize contemporary organic remains and/or find them in various stages of fossilization), we have not yet encountered any indisputable reason to deny that what we have been calling projective evidence simply represents additional data for which the hypothesis of organic fossil origins more and more clearly provides the best or only explanation.

But forcing our projective evidence into such an abductive mold simply serves to obscure important differences between it and the more stereotypically hypothetico-deductive variety.[37] Notice that in the case of the atomic hypothesis or general relativity (or for that matter, of fossil origins given only the evidence available in the early 18th Century), it is not even *open to us* to see a theoretical claim about the constitution of nature as supported by projection from events or processes we are able to observe more directly: although the behavior of billiard balls and rubber sheets are simple physical analogies we use to help *illustrate* some important characteristics of atoms or spacetime, they do not serve as some sort of inductive basis from which contemporary physicists actually *project* the causes of observed physical phenomena like Brownian motion or gravitational lensing. By contrast, we do not think the fossilization processes that operated in the distant past are simply analogous to or like those we study in the field and lab in various important or illuminating respects, but instead that these just *are* the very processes that produced fossils in the distant past and continue to do so in the present. The suggestion that contemporary physicists should study macroscopic systems of orbiting and colliding rigid objects to try to understand the atomic constitution of matter is absurd in a way that taphonomy is anything but an absurd undertaking for modern paleontology.[38] Thus, the fact that our reasoning in support of the organic origins of fossils is even *amenable to* construal as a kind of inductive projection in the first place represents a significant difference between it and what we might think of as a more fundamentally or irreducibly abductive form of justification.

A sufficiently determined objector might insist that the suggested difference between fundamentally projective and abductive empirical support is illusory, because such projective considerations are *always* an element of our abductive justifications in any case. That is, she suggests, when we think that a theory offers the best explanation of the phenomena, this is in part because in the world of events and processes we do know most directly causes *like* the one we are hypothesizing produce effects *like* the ones we observe: interference patterns like those made by light are produced by waves, changes in motion like those we see in Brownian movement are produced by collisions, or whatever. Alternatively, she might say that a sufficiently *abstract* characterization of the processes in question (e.g., mechanical collisions, wave transmission) allows us to see the interactions among billiard balls and Brownian motion as instances of a single phenomenon, and therefore to regard our beliefs as projected inductively from one case directly to the other. These will rightly strike many as dubious construals of the evidential foundations for our best theories about the constitution of matter or spacetime, but notice that even if we were to accept them for the sake of the argument, they would imply only that the difference between the two sorts of cases is one of degree. That is, in both sorts of cases we are understanding a target system (fossilization in the Pleistocene, the structure of matter, the transmission of light) by inductively projecting features of a model system that is considerably more familiar and/or accessible (fossilization in the present, billiard balls, water waves), but in the case of fossilization we have vastly more justifiable confidence in both the breadth and depth of continuity in relevant features between target and model. That is, we quite reasonably believe the chances that the hydrodynamic transportation of bones, or the effects of scavenging, or the processes of mineralization operated significantly differently in the Pleistocene than they do at present to be simply orders of magnitude lower than the chances of significant differences arising between the mechanical properties of billiard balls and atoms, or water waves and light, or rubber sheets and spacetime. Thus, even if we accept that interaction among atoms and billiard balls are both instances of ‘mechanical collisions’ or that light and water are both transmitted as ‘waves’, we think the potential and actual differences between the instances in question of these abstract kinds are radically deeper, broader, more numerous, more substantial, and more potentially significant than those between fossilization processes like hydrodynamic transport, scavenging, and mineralization as they operated in the Pleistocene and in the modern era. Indeed, it is the depth and significance of this very difference which leads us to want to say that atoms and spacetime are simply *analogous to or like* billiard balls and rubber sheets in some important respects, but fossilization just *is* what contemporary taphonomists reproduce in the lab and explore in the field.

The claim here is not, of course, that *any* scientific hypothesis whose support includes evidence that can reasonably be described as a kind of inductive projection is therefore automatically well-confirmed or belief-worthy—as always, this will depend on the quality and quantity of the inductive support and the breadth and depth of the parallels between the conditions under which the relevant inductive evidence was accumulated and those into which it is being projected. To take a simple example, the existence of so-called “rock varnish” or “desert varnish” on rocks on the surface of Mars provides only very weak projective evidence for the existence of bacterial life on that planet. Not only does the role of bacteria in producing rock varnish on our own planet remain unclear, but we know almost nothing about the depth and breadth of the parallels between the conditions under which this distinctive pattern of coloration was formed here on Earth and those under which it would have had to have been produced in the very different environment of the Martian regolith.[39] By contrast, our confidence in projecting the operation of fossilization processes into the distant past rests not only on the experimental demonstration that the combination of such processes in fact produces fossils very much like those we encounter in nature from organic remains, but also on an extensive knowledge of the wide range of conditions, locations, and circumstances under which such processes operate in the present day. Our projective evidence is so powerful in the case of organic fossil origins in part because the assumptions required for this projection are comparatively minimal: most fundamentally, we are simply assuming that the processes we have discovered to be taking place constantly all around us have been ongoing for quite some time.

Understanding how this distinctive challenge for projective forms of evidence can sometimes be convincingly overcome, however, also helps us to identify the most important virtue this sort of evidence enjoys over its abductive counterpart, especially with respect to the problem of unconceived alternatives. After all, the sort of projective evidence we have discussed here is quite obviously vulnerable to a fairly precise analogue of the original problem of unconceived alternatives with which we began: even if we show that some existing process or combination of processes *can* produce a given effect, this is far from entailing that it was *actually* this process rather than some (possibly unconceived) alternative that produced the effect in a particular instance. Similarly, the demonstration that some phenomenon could *possibly* have been produced by *some* tortured combination of known processes and effects does not automatically warrant the belief that this is in fact how it was produced. But a sufficiently powerful case for projecting the operation of a process into other times and places can nonetheless create an affirmative *challenge* for the suggestion that some alternative process (unconceived or otherwise) might actually be responsible for an observed effect. The case for projecting taphonomic processes into past environments is sufficiently strong, for example, that if we suppose some unconceived alternative process to be responsible for the fossils we have uncovered in nature, it seems that we will then have to explain why the taphonomic processes we have investigated in such detail in the field and lab have *failed* to produce fossils over geological time and/or where *those* fossils have gone! This advantage of a sufficiently strong and convincing body of projective evidence would seem to be unavailable to any abductive counterpart no matter how otherwise extensive or impressive it is. The larger point here is simply that projective evidence offers a fundamentally different kind of support than does its abductive counterpart, with a different set of corresponding virtues *and* liabilities. Not only do we miss these differences by forcing projective evidence into an abductive mold, but we also thereby threaten to obscure the role played by having *both* distinctive kinds of evidence in so radically reducing our vulnerability to the problem of unconceived alternatives in this particular case.

It is worth pointing out, however, that this distinctive combination of types of evidence does not seem to be equally available or attainable in every area of science. In fact, the contrasts we have considered seem likely to systematically favor the evidential position of some types of scientific inquiry over others, in particular, the investigation of many hypotheses in what are sometimes called 'historical' sciences like geology, paleontology, cosmology, and evolutionary biology. For it is surely in such historical sciences that we should expect the frequent recurrence of the same evidential pattern witnessed in this case, in which an hypothesis initially confirmed primarily or exclusively by the sort of abductive evidence available in support of contemporary claims about the minute constitution of matter or the nature of spacetime can serve as an impetus towards a more detailed exploration of ongoing processes that ultimately *also* provides support of the distinctively projective variety that contemporary taphonomy provides for the hypothesis of organic fossil origins.

It is therefore striking to note that in recent work Derek Turner has argued in considerable detail that our epistemic position will typically be substantially *worse* in such historical sciences investigating the distant past than in 'experimental' sciences investigating tiny or otherwise inaccessible parts of the world, for two fundamental reasons: first, the targets of experimental science are at least *still around* and waiting patiently for us as we develop increasingly sophisticated techniques for poking, prodding, and manipulating them to see how they respond, and second, in experimental sciences our background theories characteristically tell us how to do this better and better over time to generate additional evidence, while in historical sciences our background theories instead tell us precisely how evidence concerning the targets of our investigation is continuously degraded and destroyed by the passage of time. Turner begins a chapter entitled "The Colors of the Dinosaurs" with this powerful illustration:

> In my study, I have a black-and-white photograph of my grandfather as a young man, standing in front of a house holding a lunchbox. I sometimes wonder what, if anything, was in the lunchbox. That is a simple question about the past that no one will ever be able to answer. Many questions in

> historical science are like that: for instance, asking about the colors of the dinosaurs is just like asking what was in my grandfather's lunch box. In this chapter, I argue that these unanswerable questions…are more common in historical science than in experimental science.[40]

Although Turner elsewhere[41] repeats the claim that we will never know the colors of the dinosaurs, he here makes the epistemic predicament of the historical sciences especially vivid. So vivid, in fact, that I could not help but to be reminded of it when I recently opened the pages of the *New Scientist* to find the headline "Feathered Dinosaurs Show Their True Colors".[42] It turns out that we can accurately predict the colors of birds by determining the shape and arrangement of their melanosomes—microscopic, color-bearing cell structures—and we are able to determine the shape and arrangement of fossilized melanosomes from specimens of feathered dinosaurs.[43] I cannot resist pointing out that the evidence in support of this claim takes the form of the straightforward inductive projection we have been considering here: we know what colors are produced by particular arrangements of melanosomes in contemporary birds, and on that basis we are prepared to project the colors of long-extinct dinosaurs from the arrangements of *their* melanosomes. To be sure, Turner warns us[44] of the dangers of relying on observable analogues and points out cases in which such analogies have led us astray, but as in the case of fossilization processes taphonomists do not here seem to be relying on analogies in the first place (e.g. "most big herbivores—elephants, rhinoceroses, and hippopotamuses—have dull grayish colors. Perhaps the same was true of the big herbivores of the Mesozoic"[45]) but instead projecting the operation of the very same processes they have found to be causally responsible for the colors of various organisms in the present into distant times and places. Understanding the projective character of this evidence helps us to see that the background theories of taphonomy do not *just* tell us how fossilization degrades information over time as Turner emphasizes, but also when, where, and how some kinds of information are *preserved* by taphonomic processes. If we were to generalize from the cases considered here, we might conclude (contra Turner) that we will be systematically *better* off, epistemically speaking, in the historical sciences than in their experimental counterparts because of the increased availability of projective evidence. I suspect that the real lesson to be learned here, however, is just that comparisons like experimental versus historical science or observable versus unobservable entities are simply more-and-less effective proxies for what really matters, which is the *type(s) of evidence* we typically have in support of any particular claim. While it seems right to think that abductive evidence will lead us to projective evidence more often in historical sciences than elsewhere, it is the projective character of the evidence and not the historical character of the science that really makes a difference.

5. Conclusion

It is important to stress that the availability of strong projective confirmation to supplement an existing body of abductive evidence in the case of the hypothesis of organic fossil origins is simply an illustration and not an analysis of what distinguishes some contexts of scientific confirmation from others with respect to the problem of unconceived alternatives, for there are surely other differences of epistemic context that will also have considerable bearing on our vulnerability to the problem. Even if we restrict our attention to abductive forms of evidence, for example, it seems that there is a profound difference in the vulnerability to the problem of unconceived alternatives of theoretical claims regarding, say, the origins of fossils, the emergence of multicellular organisms, or the evolution of sexual reproduction as compared with that of claims regarding, say, the constitution of matter or light, or the structure of spacetime instead, surely in large part because (as thinkers like Rom Harre,[46] Peter Lipton,[47] and Christián Carman[48] have emphasized) the fundamental ontological framework is itself up for grabs in the latter contexts of theorizing in a way it is not in the former. (Who would ever have supposed that wave-particle duality was even one of the options for the nature of light and matter before the emergence of quantum mechanics, for example?) We need only recall Darwin's bombshell, however, to remind ourselves that even mature and well-developed historical sciences are anything but immune from the problem of unconceived alternatives, that important questions of fundamental ontology can arise in such sciences as well, and to immunize ourselves against hasty generalizations about general types or even specific branches of science. From this one case we can conclude only that there are important differences between epistemic contexts in their vulnerability to Duhem's original concern about unconceived alternatives and that we are only beginning to explore them. It is nonetheless these differences we will need to more fully appreciate if we are to understand both why evidently well-supported scientific hypotheses have repeatedly been overturned in the course of further inquiry and which contemporary scientific claims we should regard as entitled to greater or lesser degrees of our credence.

It might seem that all this invites us to return to our motivating contrast between the evidential situation of the hypothesis of organic fossil origins in the early 18th Century and in the present day to search for some precise point at which the belief in the organic origin of fossils switched over from rationally precluded to rationally obligatory on the basis of the accumulating collection of fundamentally projective evidence available to supplement its existing body of impressive abductive support. But of course it is a mistake to suppose that any such point must exist: we have surely learned that it is prudent to encourage a variety of levels of tolerance for epistemic risk among the members of a scientific community, and belief is not itself a bivalent, on-or-off epistemic attitude in any case. What we have considered here are elements of an extended historical process by which a suggestive hypothetical possibility has become what certainly appears to be a secure article of scientific knowledge by the accumulation of a distinctive combination of forms of empirical evidence. Just as there is no non-arbitrary precise answer to the question of at what exact point the remains of an organism become a fossil, there is no non-arbitrary precise answer to when the amount or proportion of projective evidence suffices to change a scientific hypothesis from rationally precluded to rationally obligatory. But for all that, there are rationally unjustified and rationally obligatory beliefs just as there are bones and fossils. In both cases, we have discovered extended historical processes transforming one thing into another, and the best we can do is strive to understand the constituent elements and dynamical features of those processes as well as we possibly can: organic remains and fossils exist along a continuum of transformation, and so, I suggest, do scientific hypotheses themselves.

Acknowledgments

It is a pleasure to acknowledge exceedingly useful discussions of the material in this essay with Peter Lipton, Jeff Barrett, Pen Maddy, Elliott Sober, Kevin Zollman, Gillian

Barker, John Norton, and audiences at Oberlin College, the Center for History and Philosophy of Science at the University of Pittsburgh, Cambridge University, the University of Konstanz, and UC San Diego, as well as many of the participants and attendees of the 2009 &HPS2 Conference at Notre Dame, the 2009 meeting of the European Philosophy of Science Association, a 2009 symposium on Unconceived Alternatives at the Erwin Schrödinger International Institute for Mathematical Physics and the Institute Vienna Circle, and especially the 2010 Henle Conference at Saint Louis University (where Derek Turner delivered a very useful set of comments). This essay is dedicated to the memory of Peter Lipton, who always asked the right questions.

Notes

[1] J. S. Mill, *A System of Logic, Ratiocinative and Inductive, Being a Connected View of the Principles of Evidence and the Methods of Scientific Investigation* (New York: Longmans, Green, and Co., 1900 [1867]), 328.

[2] P. Duhem, *The Aim and Structure of Physical Theory*, translated from the 2nd ed. By P. P. Wiener, originally published as *La Théorie Physique: Son Objet, et sa Structure* (Paris: Marcel Rivièra & Cie.) (Princeton: Princeton University Press, 1954 [1914]), 189-190.

[3] A. Shimony, "Scientific Inference," in *The Nature and Function of Scientific Theories*, vol. 4 of the University of Pittsburgh series in the Philosophy of Science, ed. R. G. Colodny (Pittsburgh: University of Pittsburgh Press, 1970).

[4] L. Sklar, "Do Unborn Hypotheses Have Rights?", *Pacific Philosophical Quarterly* 62 (1981), 17-29, and L. Sklar, *Theory and Truth* (New York: Oxford University Press, 2000).

[5] J. Earman, *Bayes or Bust? A Critical Examination of Bayesian Confirmation Theory* (Cambridge, MA: MIT Press, 1992).

[6] P. K. Stanford, "Refusing the Devil's Bargain: What Kind of Underdetermination Should We Take Seriously?", *Philosophy of Science 68* (2001), S1-S12; P. K. Stanford, *Exceeding Our Grasp: Science, History, and the Problem of Unconceived Alternatives* (New York: Oxford University Press, 2006); P. K. Stanford, "Scientific Realism, the Atomic Theory, and the Catch-All Hypothesis: Can We Test Fundamental Theories Against All Serious Alternatives?", *British Journal For The Philosophy of Science* 60 (2009), 253-269.

[7] Stanford, *op. cit*., 2006, Ch. 2.

[8] Cf. Stanford, *op. cit*., 2006, 32-33. In this same chapter I also address the natural holist rejoinder that *all* of our beliefs are confirmed only by serving as part of a network of interconnected hypotheses (the famous Quinean 'web of belief') that best systematizes and organizes our perceptual experience as a whole.

[9] M. Rudwick, *The Meaning of Fossils: Episodes in the History of Paleontology*, 2nd ed. (New York: Neale Watson Academic Publications, Inc., 1976), see esp. Chs. 1-2.
[10] *Ibid.*, 19.
[11] *Ibid.*, 24-25.
[12] *Ibid.*, 26, 33-34.
[13] *Ibid.*, 35.
[14] *Ibid.*, 45.
[15] *Ibid.*, 56.
[16] *Ibid.*, 53-56, 74-75.
[17] All quotations from Lister are from his 1678 *History of English Animals* or 1685-92 *The History of Shells*. Both works are quoted and fully cited in Rudwick, *ibid*, 61-63, but Rudwick's text makes it difficult to determine which quotations appear in which work.
[18] Rudwick, *op. cit.*, 64.
[19] *Ibid.*, 81.
[20] *Ibid.*, 65.
[21] *Ibid.*, 84.
[22] J. A. Efremov, "Taphonomy: A New Branch of Paleontology", *Pan-American Geologist* 74 (1940), 85.
[23] P. Shipman, *Life History of a Fossil: An Introduction to Taphonomy and Paleoecology* (Cambridge, MA: Harvard University Press, 1981), 100.
[24] The neglect of such projective evidence in science by much of contemporary confirmation theory is addressed in somewhat more detail in P. K. Stanford, "Projective Evidence and the Heterogeneity of Scientific Confirmation" (forthcoming in *Philosophy of Science*) using this same example of taphonomic research.
[25] Shipman, *op. cit.*, 103.
[26] *Ibid.*, 30-31.
[27] *Ibid.*, 31.
[28] *Ibid.*, 21-22.
[29] *Ibid.*, 171-172.
[30] *Ibid.*, 181-182.
[31] J. H. Oehler and J. W. Schopf, "Artificial Microfossils: Experimental Studies of Permineralization of Blue-Green Algae in Silica", *Science* 174 (1971), 1229.
[32] D. Martin, D. E. G. Briggs, and R. J. Parkes, "Experimental Mineralization of Invertebrate Eggs and the Preservation of Neoproterozoic Embryos", *Geology* 31 (2003), 39.
[33] D. E. G. Briggs and A. Kear, "Fossilization of Soft Tissue in the Laboratory", *Science* 259 (1993), 1439.
[34] E.C. Raff, J. T. Villinski, F. R. Turner, P. C. J. Donoghue, and R. A. Raff, "Experimental Taphonomy Shows the Feasibility of Fossil Embryos", *Proceedings of the National Academy of Sciences* 103 (2006), 5846-5851.
[35] Rudwick, *op. cit.*, 88.
[36] *Ibid.*, 89.
[37] For a somewhat more detailed discussion of what I call the "consequentialist" mold typical of much contemporary confirmation theory and the reasons to resist forcing our projective evidence into such a mold, see P. K. Stanford, "Projective Evidence and the Heterogeneity of Scientific Confirmation" (forthcoming in *Philosophy of Science*).
[38] This is not to say there was *never* a time at which the behavior of atoms was projected from that of macroscopic physical objects, but this is simply not the case in contemporary physical theory. This contrast suggests in turn, of course, that the mere presence of *some* amount or variety of projective evidence does not allow us to simply dismiss the problem of unconceived alternatives as unserious (see also below).
[39] See B. DiGregorio, "Martian Sheen: Life on the Rocks", *New Scientist* 2747 (2010): 40-43.
[40] D. Turner, *Making Prehistory: Historical Science and the Scientific Realism Debate* (Cambridge: Cambridge University Press, 2007), 37.
[41] *Ibid.*, 3, 46.
[42] J. O'Donoghue, "Feathered Dinosaurs Show Their True Colors", *New Scientist* 2745 (January 27, 2010), 12.

[43] F. Zhang, S. L. Kearns, P. J. Orr, M. J. Benton, Z. Zhou, D. Johnson, X. Xu, and X. Wang, "Fossilized Melanosomes and the Colour of Cretaceous Dinosaurs and Birds", *Nature* 463 (2010), 1075-1078.
[44] Turner, *op. cit.*, 85ff.
[45] *Ibid.*, 46.
[46] R. Harré, *Varieties of Realism: A Rationale for the Natural Sciences* (Oxford: Blackwell, 1986); R. Harré, "From Observability to Manipulability: Extending the Inductive Arguments for Realism", *Synthese* 108 (1996), 137-155.
[47] Personal communication.
[48] C. Carman, "The Electrons of the Dinosaurs and the Center of the Earth", *Studies in History and Philosophy of Science* 36 (2005), 171-174.