Stephen Jay Gould: *Dinosaur in a Haystack*

THE FASHION INDUSTRY thrives on our need to proclaim an identity from our most personal space. For academics, who by stereotype (though not always in actuality) scorn the sartorial mode, office doors serve the same function. Professorial entranceways are festooned with testimonies of deepest beliefs and strongest commitments. We may, as a profession, have a deserved reputation for lengthy and tendentious proclamation, but our office doors feature the gentler approach of humor or epigram. The staples of this genre are cartoons (with Gary Larson as the unchallenged *numero uno* for scientific doors), and quotations from gurus of the profession.

Somehow, I have never been able to put someone else's cleverness so close to my heart or soul. I wear white T-shirts and, though I wrote the preface to one of Gary Larson's *Far Side* collections, I would never identify my portal with his brilliance. But I do have a favorite quotation – one worth dying for, one fit for shouting from the housetops (if not for inscription on the doorway).

My favorite line, from Darwin of course, requires a little explication. Geology, in the late eighteenth century, had been deluged with a rash of comprehensive, but mostly fatuous, "theories of the earth" – extended speculations about everything, generated largely from armchairs. When the Geological Society of London was inaugurated in the early nineteenth century, the founding members overreacted to this admitted blight by banning theoretical discussion from their proceedings. Geologists, they ruled, should first establish the facts of our planet's history by direct observation – and then, at some future time when the bulk of accumulated information becomes sufficiently dense, move to theories and explanations.

Darwin, who had such a keen understanding of fruitful procedure in science, knew in his guts that theory and observation are Siamese twins, inextricably intertwined and continually interacting. One cannot perform first, while the other waits in the wings. In mid-career, in 1861, in a letter to Henry Fawcett, Darwin reflected on the false view of earlier geologists. In so doing, he outlined his own conception of proper scientific procedure in the best one-liner ever penned. The last sentence is indelibly impressed on the portal to my psyche.

> About thirty years ago there was much talk that geologists ought only to observe and not theorize; and I well remember someone saying that at this rate a man might as well go into a gravelpit and count the pebbles and describe the colors. How odd it is that anyone should not see that all observation must be for or against some view if it is to be of any service!

The point should be obvious. Immanuel Kant, in a famous quip, said that concepts without percepts are empty, whereas percepts without concepts are blind. The world is so complex; why should we strive to comprehend with only half our tools. Let our minds play with ideas; let our senses gather information; and let the rich interaction proceed as it must (for the mind processes what the senses gather, while a disembodied brain, devoid of all external input, would be a sorry instrument indeed).

Yet scientists have a peculiar stake in emphasizing fact over theory, percept over concept – and Darwin wrote to Fawcett to counteract this odd but effective mythology. Scientists often strive for special status by claiming a unique form of "objectivity" inherent in a supposedly universal procedure called *the* scientific method. We attain this objectivity by clearing the mind of all preconception and then simply seeing, in a pure and unfettered way, what nature presents. This image may be beguiling, but the claim is chimerical, and ultimately haughty and divisive. For the myth of pure perception raises scientists to a pinnacle above all other struggling intellectuals, who must remain mired in constraints of culture and psyche.

But followers of the myth are ultimately hurt and limited, for the immense complexity of the world cannot be grasped or ordered without concepts. "All observation must be for or against some view if it is to be of any service." Objectivity is not an unobtainable emptying of mind, but a willingness to abandon a set of preferences – for or against some view, as Darwin said – when the world seems to work in a contrary way.

This Darwinian theme of necessary interaction between theory and observation gains strong support from a scientist's standard "take" on the value of original theories. Sure, we love them for the usual "big" reasons – because they change our interpretation of the world, and lead us to order things differently. But ask any practicing scientist, and you will probably get a different primary answer – for we are too busy with the details and rhythms of our daily work to think about ultimates very often. We love original theories because they suggest new, different, and tractable ways to make observations. By posing different questions, novel theories expand our range of daily activity. Theories impel us to seek new information that becomes relevant only as data either "for or against" a hot idea. Data adjudicates theory, but theory also drives and inspires data. Both Kant and Darwin were right.

I bring up this personal favorite among quotations because my profession of paleontology has recently witnessed such a fine example of theory confirmed by data that no one ever thought of collecting before the theory itself demanded such a test. (Please note the fundamental difference between demanding a test and guaranteeing the result. The test might just as well have failed, thus dooming the theory. Good theories invite a challenge but do not bias the outcome. In this case, the test succeeded twice, and the theory has gained strength.) Ironically, this particular new theory would have been anathema to Darwin himself, but such a genial and generous man would gladly, I am sure, have taken his immediate lumps in exchange for such a fine example of his generality about theory and observation, and for the excitement of any idea so full of juicy implications.

We have known since the dawn of modern paleontology that short stretches of geological time feature extinctions in substantial percentages of life – up to 96 percent of marine invertebrate species in the granddaddy of all such events, the late Permian debacle, some 225 million years ago. These "mass extinctions" were originally explained, in a literal and commonsense sort of way, as products of catastrophic events, and therefore truly sudden. As Darwin's idea of gradualistic evolution replaced this earlier catastrophism, paleontologists sought to mitigate the evidence of mass dying with a reading more congenial to Darwin's preference for the slow and steady. The periods of enhanced extinction were not denied – impossible in the face of such evidence – but they were reinterpreted as more spread out in time and less intense in effect, in short as intensifications of ordinary processes, rather than impositions of true and rare catastrophes.

In his *Origin of Species* (1859), Darwin rejected "the old notion of all the inhabitants of the earth having been swept away at successive periods by catastrophes" – as well he might, given the extreme view of total annihilation, with its anti-evolutionary implication of a new creation to start life again. But Darwin's own preferences for gradualism were equally extreme and false: "We have every reason to believe … that Species and groups of species gradually disappear, one after another, first from one spot, then from another, and finally from the world." Yet Darwin had to admit the apparent exceptions: "In some cases, however, the extermination of whole groups of beings, as of the ammonites towards the close of the secondary period, has been wonderfully sudden."

We now come to the central irony that inspired this essay. So long as Darwin's gradualistic view of mass extinction prevailed, paleontological data, read literally, could not refute the basic premise of gradualism – the "spreading out" of extinctions over a good stretch of time before the boundary, rather than a sharp concentration of disappearances right at the boundary itself. For the geological record is highly imperfect, and only a tiny fraction of living creatures ever become fossils. As a consequence of this imperfection, even a truly sudden and simultaneous extinction of numerous species will be recorded as a more gradual decline in the fossil record. This claim may sound paradoxical, but consider the following argument and circumstance:

Some species are very common and easily preserved as fossils; we may, on average, find specimens in every inch of strata. But other species will be rare and poorly preserved, and we might encounter their fossils only once every hundred feet or so. Now suppose that all these species died suddenly at the same time, after four hundred feet of sediment had been deposited in an ocean basin. Would we expect to find the most direct evidence for mass extinction-that is, fossils of all species through all four hundred feet of strata right up to the very top of the sequence? Of course not.

Common species would pervade the strata, for we expect to find their fossils in every inch of sediment. But even if rare species live right to the end, they contribute a fossil only every hundred feet or so. In other words, a rare species may have lived through four hundred feet, but its last fossil may be entombed one hundred feet below the upper boundary. We might then falsely assume that this rare species died out after three fourths of the total time had elapsed.

Generalizing this argument, we may assert that the rarer the species, the more likely that its last fossil appears in older sediments even if the species actually lived to the upper boundary. If all species died at once, we will still find a graded and apparently gradualistic sequence of disappearances, the rare species going first and the common forms persisting as fossils right to the upper boundary. This phenomenon – a classic example of the old principle that things are seldom what they seem and that literal appearances often obscure reality – even has a name: the Signor-Lipps effect, to honor two of my paleontological buddies, Phil Signor and Jere Lipps, who first worked out the mathematical details of how a literal petering out might represent a truly sudden and simultaneous disappearance.

We can now sense the power of Darwin's argument about needing theories to guide observations. We say, in our mythology, that old theories die when new observations derail them. But too often – I would say usually – theories act as straitjackets to channel observations toward their support and to forestall potentially refuting data. Such theories cannot be rejected from within, for we will not conceptualize the disproving observations. If we accept Darwinian gradualism in mass extinction, and therefore never realize that a graded series of fossil disappearances might, by the Signor-Lipps effect, actually represent a sudden wipeout, how will we ever come to consider the catastrophic alternative? For we will be smugly satisfied that we have "hard" data to prove gradualistic decline in species numbers.

New theories work upon this conceptual lock as Harry Houdini reacted to literal straitjackets. We escape by importing a new theory and by making the different kinds of observations that any novel outlook must suggest. I am not making an abstract point or waving arms for my favorite Darwinian motto. Two lovely examples with the same message have recently been published by a pair of my closest colleagues: studies of ammonites and dinosaurs through the last great extinction.

Anyone who keeps up with press reports on hot items in science knows that a new catastrophic theory of mass extinction has illuminated the paleontological world (and graced the cover of *Time* magazine) during the past decade. In 1979 the father-son (and physicist-geologist) team of Luis and Walter Alvarez published, with colleagues Frank Asaro and Helen Michel, their argument and supporting data for extraterrestrial impact of an asteroid or a comet as the cause of the Cretaceous-Tertiary extinction, the most recent of the great mass dyings, and the time of departure for dinosaurs along with some 50 percent of marine invertebrate species.

This proposal unleashed a furious debate that cannot be summarized in a page, much less an entire essay, or even a book. Yet I think it fair to say that the idea of extraterrestrial impact has weathered this storm splendidly and continually increased in strength and supporting evidence. At this point, very few scientists deny that an impact occurred, and debate has largely shifted to whether the impact caused the extinction *in toto* (or only acted as a coup de grace for a process already in the works), and whether other mass extinctions may have a similar cause.

But paleontologists, with very few exceptions, reacted negatively at first (to say the least) – and Luis Alvarez, a virtual model for the stereotype of the self-assured physicist, was fit to be tied. (Luis, in retrospect, was also mostly right, so I forgive his fulminations against my profession. I, if I may toot my horn, was among his few initial supporters, but not for the right reason of better insight into the evidence. Catastrophic extinction simply matched my idiosyncratic preference for rapidity, born of the debate over punctuated equilibrium – see essay 8.) After all, my colleagues had been supporting Darwinian gradualism for a century, and the fossil record, read literally, seemed to indicate a petering out of most groups before the boundary. How could an impact cause the extinction if most species were dead already?

But the extraterrestrial impact theory soon proved its mettle in the most sublime way of all – by Darwin's criterion of provoking new observations that no one had thought of making under old views. The theory, in short, engendered its own test and broke the straitjacket of previous certainty.

My colleagues may have disliked the Alvarez hypothesis with unconcealed vigor, but we are an honorable lot and, as debate intensified and favorable evidence accumulated, paleontologists had to take another look at their previous convictions. Many new kinds of observations can be made, but let us focus on the simplest, most obvious, and most literal example. In the light of new prestige for impact and sudden termination, the Signor-Lipps argument began to sink in, and paleontologists realized that catastrophic wipeouts might be recorded as gradual declines in the fossil record.

How, then, to break the impasse produced by this indecisive literal appearance of petering out? Many procedures, some rather subtle and mathematical, have been proposed and pursued, but why not start with the most direct approach? If rare species actually lived right to the impact boundary, but have not yet been recorded from the uppermost strata, why not look a whole lot harder? The obvious analogy to the usual cliché suggests itself. If I search for a single needle in a haystack by sampling ten handfuls of hay, I have very little chance of locating the object. But if I take apart the stack, straw by straw, I will recover the needle. Similarly, if I really search every inch of sediment in every known locality, I might eventually find even the rarest species right near the boundary – if it truly survived.

This all seems rather obvious. I cannot possibly argue that such an approach could not have been conceptualized before the Alvarez hypothesis. I cannot claim that ideological blinders of gradualism made it impossible even to imagine pulling apart the haystack rather than sampling a few handfuls. But this example becomes so appealing precisely through its entirely pedestrian character. I could cite many fancy cases of original theories that open entirely new worlds of observation; think of Galileo's telescope and all the impossible phenomena thus revealed. In this case, the Alvarez theory suggested little more than hard work.

So why wasn't the effort expended before? Paleontologists are an industrious lot; we have faults aplenty, but laziness in the field does not lie among them. We do love to find fossils – the reason why most of us entered the profession in the first place. We didn't scrutinize every inch of sediment for the most basic of all scientific reasons. Life is short and the world is immense; you can't spend your career on a single cliff-face. The essence of science is intelligent sampling, not sitting in a single place and trying to get every last one. Under Darwinian gradualism, intelligent sampling followed the usual method of handful-from-the-haystack.

The results obtained matched the expectations of theory, and conceptual satisfaction (one might say "sloth" in retrospect) set in. No impetus existed for the much more laborious technique of dismember-the-entire-haystack, a quite unusual approach in science. We could have worked by dismemberment, but we didn't, and had no reason to do so. The Alvarez theory made this unusual approach necessary. The new idea forced us to observe in a different way. "All observation must be for or against some view if it is to be of any service."

Consider two premier examples – the best-known marine and the best-known terrestrial groups to disappear in the Cretaceous-Tertiary extinction: ammonites and dinosaurs. Both had been prominently cited as support for gradual extinction toward the boundary. In each case, the Alvarez hypothesis inspired a closer look using the inch-by-inch method; and in each case this greater scrutiny yielded evidence of persistence to the boundary, and potentially catastrophic death.

Ammonites are cephalopods (mollusks classified in the same group as squids and octopuses) with coiled external shells closely resembling those of their nearest living relative, the chambered nautilus. Ammonites were a prominent, often dominant, group of marine predators, and their beautiful fossil shells have always been prized by collectors. They arose in mid-Paleozoic times and had nearly become extinct twice before in two other mass dyings at the end of the Permian and the close of the Triassic periods. But a lineage or two had scraped by each time. At the Cretaceous-Tertiary boundary, however, all lineages succumbed and, to cite Wordsworth from another context, there "passed away a glory from the earth."

My friend and colleague Peter Ward, paleontologist from the University of Washington, is one of the world's experts on ammonite extinction, and a vigorous, committed man who adores fieldwork and could never be accused of laziness on the outcrop. Peter didn't care much for Alvarez at first, largely because his ammonites seemed to fade out and disappear entirely some thirty feet below the boundary at his favorite site, the cliffs of Zumaya on the Bay of Biscay in Spain. In 1983, Peter wrote an article for *Scientific American* titled "The extinction of the ammonites." He stated his opposition to the Alvarez theory, then so new and controversial, at least as an explanation for the death of ammonites:

> The fossil record suggests, however, that the extinction of the ammonites was a consequence not of this catastrophe but of sweeping changes in the late Cretaceous marine ecosystem … Studies of the fossils from the stratigraphic sections at Zumaya in Spain suggest they became extinct long before the proposed impact of the meteoritic body.

But Peter, as one of the smartest and most honorable men I know, also acknowledged the limits of such "negative evidence." A conclusion based on *not* finding something provides the great virtue of unambiguous potential refutation. Peter wrote: "This evidence is negative and could be overturned by the finding of a single new ammonite specimen."

Without the impact hypothesis, Peter would have had no reason to search those upper thirty feet of section with any more care. Extinctions were supposed to be gradual, and thirty feet of missing ammonites made perfect sense, so why look any further? But the impact hypothesis, with its clear prediction of ammonite survival right up to the boundary itself, demanded more intense scrutiny of the thirty-foot haystack. In 1986, Peter was still touting sequential disappearance: "Ammonites … appear to have become extinct in this basin well before the K/T [Cretaceous-Tertiary] boundary, supporting a more gradualistic view of the K/T extinctions."

But Peter and his field partners, inspired by Alvarez (if only by a hope of disproving the impact hypothesis), worked on through the haystack: "The remaining part of the Cretaceous section was well exposed and vigorously searched and quarried." Finally, later in 1986, they found a single specimen just three feet below the boundary. The fossil was crushed, and they couldn't tell for certain whether it was an ammonite or a nautiloid, but this specimen did proclaim a need for even more careful search. (Since nautiloids obviously survived the extinction – the chambered nautilus still lives today – a fossil nautiloid right at the boundary would occasion no surprise.)

Peter started a much more intense search in 1987, and the ammonites began to turn up – mostly lousy specimens, and very rare, but clearly present right up to the boundary. Peter wrote in a book published in early 1992: "Finally, on a rainy day, I found a fragment of an ammonite within inches of the clay layer marking the boundary. Slowly, over the years, several more were found in the highest levels of Cretaceous strata at Zumaya. Ammonites appeared to have been present for Armageddon after all."

Peter then took the obvious next step: look elsewhere. Zumaya contained ammonites right to the end, but not copiously, perhaps for reasons of local habitat rather than global abundance. Peter had looked in sections west of Zumaya and found no latest Cretaceous ammonites (another reason for his earlier acceptance of gradual extinction). But now he extended his fieldwork to the east, toward the border of Spain and France. (Again, these eastern sections were known and had always been available for study, but Peter needed the impetus of Alvarez to ask the right questions and to develop a need for making these further observations.) Peter studied two new sections, at Hendaye on the Spanish-French border, and right on the yuppie beaches of Biarritz in France. Here he found numerous and abundant ammonites just below the boundary line of the great extinction. He writes in his 1992 book:

> After my experience at Zumaya, where years of searching yielded only the slightest evidence … near the Cretaceous-Tertiary boundary, I was overjoyed to find a score of ammonites within the last meter of Cretaceous rock during the first hour at Hendaye.

We professionals may care as much about ammonites, but dinosaurs fire the popular imagination. No argument against Alvarez has therefore been more prominent, or more persuasive, than the persistent claim by most (but not all) dinosaur specialists that the great beasts, with the possible exception of a straggler or two, had died long before the supposed impact.

I well remember the dinosaur men advancing their supposed smoking gun of a "three-meter gap" – the barren strata between the last known dinosaur bone and the impact boundary. And I recall Luis Alvarez exploding in rage, and with ample justice (for I felt a bit ashamed of my paleontological colleagues and their very bad argument). The last bone, after all, is not the last animal, but rather a sample from which we might be able to estimate the probable later survival of creatures not yet found as fossils. If my buddy throws a thousand bottles overboard and I later pick up one on an island fifty miles away, I do not assume that he only tossed a single bottle. But if I know the time of his throw and the pattern of currents, I might be able to make a rough estimate of how many he originally dropped overboard. The chance of any single animal becoming a fossil is surely much smaller than the probability of my finding even one bottle. All science is intelligent inference; excessive literalism is a delusion, not a humble bowing to evidence.

Again, as with Peter Ward and the ammonites, the best empirical approach would order a stop to the shouting and organize a massive effort to dismember the haystack by looking for dinosaur bones in every inch of latest Cretaceous rocks. *Peter* means "rock" in Latin, so maybe men of this name are predisposed to a paleontological career. Another Peter, my friend and colleague Peter Sheehan of the Milwaukee

Public Museum, has been guiding such a project for years. In late 1991 he published his much-awaited results.

Dinosaurs are almost always rarer than marine creatures, and this haystack really has to be pulled apart fragment by fragment, and over a broad area. The National Science Foundation and other funding agencies simply do not supply grant money at such a scale for projects that lack experimental glamour, whatever their importance. So Peter (Sheehan this time) cleverly availed himself of a wonderful resource that mere ammonites could never command. I will tell the story in his words:

> We co-opted the longstanding volunteer-based "Dig-a-Dinosaur" program at the Milwaukee Public Museum. Sixteen to twenty-five carefully trained and closely supervised volunteers and ten to twelve staff members were present during each of seven two-week field sessions during three summers. The primary objective of each volunteer was to search a predetermined area for all bone visible on the surface. The volunteers were arrayed in "search party" fashion across exposures so that all outcrops were surveyed systematically. Associated with the field parties were geologists whose function was to measure stratigraphic sections and identify facies.

I cannot think of a more efficient and effective way to tackle a geological haystack. Peter's personnel logged fifteen thousand hours of fieldwork and have provided our first adequate sampling of dinosaur fossils in uppermost Cretaceous rocks. Working in the Hell Creek Formation in Montana and North Dakota, they studied each environment separately, with best evidence available from stream channels and floodplains. They divided the entire section into thirds, with the upper third extending right to the impact boundary, and asked whether a steady decline occurred through the three units, leaving an impoverished fauna when the asteroid struck. Again, I will let their terse conclusion, summarizing so much intense effort, speak for itself.

> Because there is no significant change between the lower, middle, and upper thirds of the formation, we reject the hypothesis that the dinosaurian part of the ecosystem was deteriorating during the latest Cretaceous. These findings are consistent with an abrupt extinction scenario.

You can always say, "So what? T. S. Eliot was wrong; some worlds at least end with a bang, not a whimper." But such a distinction makes all the difference, for bangs and whimpers have such disparate consequences. Peter Ward sets the right theme in his final statement on the non-necessary demise of ammonites:

> Their history was one of such uncommon and clever adaptation that they should have survived, somewhere, at some great depth. The nautiloids did. It is my prejudice that the ammonites would have, save for a catastrophe that changed the rules 66 million years ago. In their long history they survived everything else the earth threw at them. Perhaps it was something from outer space, not the earth, that finally brought them down.

The true philistine may still say, "So what? If no impact had occurred, both ammonites and nautiloids would still be alive. What do I care? I had never even heard of nautiloids before reading this essay." Think about dinosaurs and start caring. No impact to terminate their still-vigorous diversity, and perhaps dinosaurs survive to the present. (Why not? They had done well for more than 100 million years, and the earth has only added another 65 million since then.) If dinosaurs survive, mammals almost surely remain small and insignificant (as they were during the entire 100 million years of dinosaurian domination). And if mammals stay so small, restricted, and unendowed with consciousness, then surely no humans emerge to proclaim their indifference. Or to name their boys Peter. Or to wonder about the heavens and the earth. Or to ponder the nature of science and the proper interaction between fact and theory. Too dumb to try; too busy scrounging for the next meal and hiding from that nasty *Velociraptor*.