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LETTERS

What's So Special About Science?

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Just south of Tanzania's border with Kenya, the teeming Serengeti Plains are sundered by a 30-mile long and 300-feet deep gash. This dramatic erosional feature is Olduvai Gorge, an iconic name in human prehistory. Seen from the air in the clear evening light, and especially on those occasions—not rare—when its rim is touched with gold, the Gorge exudes a soft, magical aura that approaches the mystical. During the height of the day, in contrast, this rugged ravine is a hell-hole of hot, rough rock, whose variegated colors are almost bleached out by the scorching intensity of the sun. This is not a place where most rational people would choose to tarry any longer than absolutely necessary. Yet, if you carefully approach the Gorge's dizzying edge at certain times of year, you will sometimes see, far below, some tiny figures delving into the hot earth at the Gorge's bottom. These are paleoanthropologists, scientists involved in uncovering evidence of the human past. For the rocks exposed in the walls of the Gorge are witnesses to almost 2 my of geological and human history, and have attracted paleontologists, archeologists, and others ever since the Gorge's discovery in the early years of the last century. Most famously, this is the place where Mary and Louis Leakey discovered the remarkable "Zinjanthropus" skull in 1959, and from which *Homo habilis*—"handy man"—was reported a few years later.

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Looking at those half-naked, sunburned figures sweating away far below, you cannot help but reflect that they hardly conform to the popular stereotype of the scientist. Ask most people for their image of a typical scientist and chances are that they will conjure up visions of a white-coated figure tending high-tech instruments in a spotless air-conditioned laboratory or covering a well-worn blackboard with elaborate mathematical formulae in an ivy-covered building on some ancient campus. And, at least to a certain extent, this is not inaccurate. Some scientists, possibly even a majority, do look and behave this way at least some of the time. But scientists are people, and they are quite as diverse as any other category of human being. Some labor in the field like those at Olduvai; others rarely leave the comfort and safety of the laboratory. What do these disparate individuals have in common? What is it that gives science its unity and sets it apart from all other forms of human endeavor?

Let us put one common misapprehension to rest right away. It is not that they are all diligently applying "the scientific method". Indeed, there *is* no single "scientific method". Scientific methods of course there are, in abundance; and methodologies lie at the heart of the immense variety of different things that scientists do. But different techniques are used for tackling different problems, and there is no particular "method" that will give you the key to all types of scientific inquiry.

The Nature of Science

Perhaps, then, if it is not a method of investigation that gives science its unity, it might be better to start with what science is *not*. And this is important, because in America today, more perhaps than in any other advanced nation, there is a widespread mistrust of science that is largely born of a lack of understanding of what science is and is not. On the one hand, we are happy to enjoy the many benefits of science; on the other, we tend to fear scientific advance or at least to look upon it askance. At one end of the negative spectrum we imagine practical disaster, as technology runs amok. At the other, we find the political imposition in schools of the tenets of creationism taught as science, as if mainstream scientific beliefs were somehow intrinsically opposed to those of religion—which they are most emphatically not. Religion is based on faith, whereas science is grounded in doubt; and although both religion and science do deal with questions of origin, the province of religion is ultimate cause, whereas the causes investigated by science are proximate ones. It seems highly unlikely that science will ever penetrate the ultimate mysteries that religion deals in—and it probably will not even seriously try, although of course it is not hard to find a scientist willing to pontificate about virtually any subject you want.

The creationist misunderstanding, in particular, stems from the notion that science is an authoritarian system of belief that tells us in absolutist terms how and what the universe is. Here the rather alienating image of the white-coated scientist, rigorously quantifying the world in the remoteness of his laboratory, does not help at all. It is, indeed, hard to imagine a more intimidating authority figure than white-coat, his clipboard covered with incomprehensible hieroglyphics that the uninitiated—you and I—will never understand. It would certainly be better if the more user-friendly image of the overheated and disheveled field worker had wider currency.

Still, either way, the pursuit is essentially the same. For all scientific knowledge, however acquired, is inherently provisional. Most scientists will readily acknowledge this reality. No scientist who thinks twice about the matter is going to claim that he or she is really in pursuit of "the truth" or has any hope of demonstrating it definitively, although this is admittedly a mindset that it is all too easy to slip into. All any honest scientist is really trying to do is to *approximate* the truth, in the realization that ultimate truth is unknowable through scientific means and that the knowledge he or she generates is invariably susceptible to modification.

This is why the familiar mantra of creationists, that "Darwinism is *only* a theory", (see the article in this issue by T. Ryan Gregory) merely shows how deeply these well-meaning people misunderstand what science is all about. For in the most profound of senses, *all* scientific knowledge is "only a theory". Religious belief is a matter of revealed truth and is thus (within interpretive limits) unchanging. Scientific belief, on the other hand, is even in principle only valid as long as it can resist attempts to show that it is wrong. Indeed, whereas science as a whole embodies a profound feeling that progress *can* be made—for otherwise, what is the point of the whole enterprise?—there is no way in which we can make scientific progress unless we can demonstrate that what we now believe is wrong or at least incomplete.

The way I like to look at it is that the core of the scientific endeavor amounts simply to the corporate effort to describe nature and its workings as accurately as possible. Some of these descriptions are very strongly supported and are unlikely to change dramatically with time. Others are shakier, and it is also an unavoidable fact that the solution of one scientific problem regularly leads to the identification of others that are at least as tricky. Throughout the history of science, the successful climbing of an intellectual summit has always revealed new peaks beckoning beyond. The upshot is that what scientists are emphatically *not* doing is steadily building up a picture of "the truth".

If this were the case, the practice of science would be rather like doing a giant jigsaw puzzle in which each correctly placed piece becomes a permanent part of a gradually emerging but still essentially static picture. By implication, the picture will at some stage be complete and from day to day what is already established will not change. However, even if there must in principle be a dead-accurate description of the world out there somewhere, like the picture on the puzzle box, science is not equipped to identify it as such. Instead, the process of science is much more like negotiating a hugely complex maze, and the history of science is littered with false starts and back-trackings. New ideas—new descriptions of nature, mostly tiny corners of it—are proposed, and once those ideas and observations are out there in the public arena, they can be tested. Very often these new notions, usually proposed to correct deficiencies identified in earlier ideas or to accommodate new data that do not fit with whatever was previously believed, will turn out to be wrong either in detail or in their entirety. The neat part, though, is that this does not matter at all. In science it is no crime to be wrong, unless you are (inappropriately) laying claim to the truth. What *matters* is that science as a whole is a self-correcting mechanism in which both new and old notions are constantly under scrutiny. In other words, the edifice of scientific knowledge consists simply of a body of observations and ideas that have (so far) proven resistant to attack and that are thus accepted as working hypotheses about nature. This may sound like a rather rough-and-ready way of proceeding; but clearly, in the mere two or three centuries that have elapsed since recognizable science began to come into existence, it has brought us a remarkably long way. Few would dispute that in this time science truly has revolutionized all of our lives in a way in which no other approach to knowledge has ever managed to do.

Falsifiability

For this system of provisional knowledge to work, it is necessary that, to the extent possible, scientific hypotheses be proposed in such a way that they are at least potentially falsifiable—provable to be wrong. Nonscientific statements about the world can simply be judged by the criterion of plausibility, which is fine in its place; but a scientific statement has to be subject to disproof if it is wrong or lacking something. It has to be one that, if wrong, can be shown to be so by more than simply assertion. Scientists should not be out to *prove* anything. Of course, many areas of science depend heavily on techniques of mathematical description, and mathematicians are frequently in search of "proofs" of one conjecture or another. But it is a mistake to confuse quantifiability with objectivity. The various branches of mathematics are essentially systems of logic that are based on axiomatic starting assumptions. And whereas scientists find the techniques of mathematical description very helpful in characterizing the world, they themselves cannot start from assumptions. They have to start from what they know about the world, in the knowledge that what they think they know is always subject to change.

That is the theory, anyway, and it applies pretty well in the experimental sciences such as physics. There, scientists generally start either from new hypotheses that they hope describe the world accurately or from established notions that seem to be becoming a little wobbly. These they test against new data garnered by experiment and observation, often expressly for the purpose. There is, however, another category of sciences, which few reasonable observers will deny are "scientific", but in which the nature of the phenomena being studied precludes those involved from taking the experimental route. These are the "historical sciences", most notably evolutionary biology. We can study the *functioning* of the hereditary molecules within each cell by conventional scientific methods of experimentation, but what we cannot test directly by setting up experiments is the *history* of those molecules: exactly how they came to be as they are, and how their properties came to be distributed in nature in the way that we observe. These are matters of history on an immensely long timescale, and those histories can never be replicated in the laboratory. Fortunately, though, there is a way around this. Experimental scientists make predictions about the outcomes of their experiments, and then compare the data gathered against those predictions. And so do evolutionary biologists. The difference is merely that, in their case, the experiments have already been made long ago.

The central prediction that emerges from evolutionary theory is based on the common descent of all life forms. For if all life is descended from a single common ancestor, then we should expect to see a "nested" pattern of resemblance among the varied descendants of that ancestor. It should be possible to represent all of life in a single branching diagram that ramifies upwards from a single ancestor at the bottom. Actually, things seem to have been a bit more complicated than this, at least at the beginning of the history of life. All life may not, in fact, have had a singular origin (and why should it; if simple self-replicating molecules could emerge once, then why not multiple times in a largely competition-free age?), and, early on, at least one significant new form of life may have risen from a combination of old ones. The important thing, though, is that we would never have realized or have begun to understand this if we had not started from a hypothesis—that all life did have a common origin—which we could test and refine by reference to the structure of the living world around us.

In any event, subsequent to the establishment of the major groups of living organisms, we do find a very strong overall signal when we compare the distribution of characteristics among the presumed descendant forms. People have realized this since time immemorial, of course. "Folk taxonomies" have long reflected the realization that the living world is organized into groups-within-groups that can be defined on the basis of characteristics that their members share; and nobody who has any familiarity with the living world has any problem distinguishing a bird from a bat or a flying fish. What science allows us to do is to move beyond such levels of generality and more precisely to specify the relationships among organisms. Under scientific scrutiny, these sometimes turn out unexpectedly; who would have thought that lungfish are more closely related to cows than they are to salmon?

Among the very few philosophers of science who have been taken at all seriously by scientists themselves was the late Sir Karl Popper, the leading proponent of the notion of falsifiability as the crux of scientific ideas. Especially in his early days, Popper took a rather dim view of evolutionary biology as science, claiming quite fairly that there are "no evolutionary laws". But here Popper was missing his own point. If scientific knowledge is provisional, as the falsifiability criterion implies, then we probably should not be looking for unvarying "laws" at all, however tempting such a pursuit might be. "Rules of thumb" might be a better term for most scientific generalizations.

Later in his career, Popper softened his stance somewhat, describing evolutionary biology as a "metaphysical research program". Whatever this actually means, it falls upon the ear as vaguely derogatory, and Popper's description was seized upon eagerly by the foes of evolution. For whatever it may actually be, metaphysics sounds like the antithesis of science. But in Popper's universe, this change of terminology actually amounted to something of a compliment, as for him it carried the implication that Darwinism provided “a possible framework for testable scientific hypotheses”. And it turns out that the unfolding of an evolutionary history is the best explanation we have—and the *only* predictive one—for the pattern of life we see around us. If the living world was created by a supernatural being, then the world is the way it is simply because that being wanted it this way. Fine, if this is what you happen to believe; just do not dress it up as science. The notion of evolution predicts the nested pattern of relationships we find in the living world; supernatural creation, on the other hand, predicts nothing. It is concepts of this latter kind that are truly untestable: and what else is faith about, after all?

Of course, this notion of falsifiability is inherently incomplete. It deals with how ideas should be posed so that they can be evaluated. But it begs an obvious question: where do the ideas, good or bad, come from in the first place? Well, there are no rules for human creativity—how could there be?—and science depends on creative thought and intuition quite as much as any other branch of human endeavor. When we consider the origin of truly new ideas in science, we are, essentially, dealing with the mysteries of human cognition. “Eureka!” is a reaction that is familiar in science (though maybe not as familiar as many of us would like!); but it is, alas, not something that can be consciously conjured up.

Science as a Collective Enterprise

So far, I have been speaking mostly of the kind of science practiced by individual scientists or by teams of them. But we should never forget that science is above all a huge worldwide collective enterprise. For whereas it is possible to imagine a world without scientists, or with many millions of them, short of a post disaster scenario it is literally impossible to imagine a world with just one. From well before the early days when the savants who founded London’s Royal Society gathered regularly to compare their observations of nature, science has been recognized as a corporate enterprise. Isaac Newton was not the first to have said, two and a half centuries ago, that if he had seen farther it was because he had stood on the shoulders of giants. But this classic remark encapsulates a basic verity of the scientific process. This is, that all science has to start from what is currently known about the world or from what is believed about it. And this in turn helps to explain why it is so difficult to put one’s finger on the origins of science itself. Science depends on an enormous body of knowledge that has been accumulated over the centuries, thanks to the efforts of countless investigators. So, given the great inertia of large bodies of anything, how does scientific change occur at all?

The most persuasive and comprehensive account of this process was published some 40 years ago by Thomas Kuhn, the only philosopher of science whose fame rivals Popper’s. Kuhn, who started life as a physicist, was acutely aware of the role of the scientific community as a whole in spurring scientific advance. In his book *The Structure of Scientific Revolutions*, Kuhn pointed out that at any one time belief in any particular area of science tends to be dominated by what he called a “paradigm”, a generally accepted explanatory framework into which new observations are incorporated as a matter of course. Such paradigms initially become dominant as large numbers of scientists are attracted away from competing forms of explanation. And they stand at the origin of new traditions of scientific research, as the new paradigm reveals new questions to be explored. As time passes, however, paradigms tend to ossify into forms of received wisdom, even as new observations about the world accumulate. The tendency among scientists will be to try to understand these within the context of the accepted paradigm; but at some point, so many anomalies will have been identified that a new explanatory framework becomes necessary. At such moments, science is ready to witness a “paradigm shift” in which the old framework is rejected in favor of a new one that can more convincingly accommodate new observations.

This is rarely an overnight process. I was fortunate enough to be studying geology in graduate school just at the moment when the new notion of “plate tectonics” was being born. At the beginning of the 1960s, it was generally believed that the basic form of the Earth’s surface was static. Of course, evidence of earth movements was abundant in the geological record, and phenomena such as the gigantic Krakatoa explosion of 1883 or the 1906 San Francisco earthquake, were only too fresh in memory. But even the largest such events were viewed as essentially local; and geologists sought local causes for them, often with enormous sophistication and ingenuity. Around the turn of the 1960s, however, a new generation of geologists began to make observations that tied earthquake zones, volcanism, rifting of continents and seafloors, mountain building, and a host of other geological phenomena to a picture of the Earth’s surface that was constantly undergoing change. It turned out that, as some mavericks had already theorized, geography is unstable after all. Instead, the continents are mobile blocks of relatively light rock floating on the heavier molten rocks below them. Oceans are formed by the rifting-apart of continental blocks, whereas the huge forces unleashed by collisions between the drifting fragments are responsible for earthquakes and mountain building, and volcanoes reflect the escape of molten material from below. If it were not for this constant and often violent process of renewal, the continental surfaces would long ago have eroded and subsided below the surface of the oceans, and there would be nowhere for terrestrial life. Thus, in a remarkably short time, a new explanatory framework was developed that provided, for the first time, a comprehensive mechanism knitting together a world of apparently diverse geological phenomena.

You might have thought that geologists would have been delighted by this intellectual unification. Not necessarily so. There was tremendous resistance to the new ideas, not just among the old guard but also among younger colleagues who remained under their influence. This is hardly surprising or even reprehensible: it takes a while to detect which way the wind is blowing, and it is tough to reject principles to which one has devoted one's career. And of course, the new field of plate tectonics certainly did not summarily invalidate the vast bulk of the detailed local observations on which other geological explanations had been founded. What is more, there is considerable inertia built into the process of scientific education. Textbooks take years to change with new knowledge, and it is remarkable how early it is in the educational process that the mindsets of young scientists become established. It is a huge responsibility for any teacher to present a view of a scientific field to students who are hearing it for the first time; for an effective teacher will almost certainly inculcate a view of the world which down the line will prove very difficult to modify in their students' minds—however much the evidence changes. Add to this that the role of doubt in the scientific process is far too rarely taught to aspiring scientists, and the potentially oppressive power of received wisdom is painfully apparent.

Still, Kuhn was undoubtedly right: paradigms must change sooner or later, as knowledge accumulates. For the piling-up of anomalous observations cannot forever be ignored and must eventually lead to the demise of inadequate explanatory frameworks, however tenaciously they linger. The history of science has borne this pattern out over and over again, and in fact, it is not necessarily only new observations that lead to paradigm shifts. For some paradigms are essentially intellectual: they are views of how science should be done and are not dependent on any specific set of observations. Indeed, in my own science of paleoanthropology, we are at this very moment in the middle of a paradigm shift of this kind.

Let me explain. When I was in graduate school, my office was a desk in a basement storeroom of a natural history museum. I would watch enviously as visiting scientists pored for hours over fossils that they pulled from the cabinets that lined the room, making reams of notes and measurements. For it seemed that these people—these initiates—knew exactly what they were doing, whereas nobody had yet taken the trouble to explain to me how to go about studying fossils. I had attended innumerable courses in vertebrate paleontology, of course, but the emphasis was usually on the instructor's interpretations of particular fossils, rather than on how they were arrived at. Eventually, I found the courage to ask a distinguished paleoanthropologist what the secret of studying fossils was. The answer? "You look at them long enough, and they speak to you." Well, yes, okay. It is true that sheer familiarity with fossils will reveal things about them that nothing else can. But as my colleague Milford Wolpoff once said, "I've spent a lot of time alone with fossils, and none of them ever said a word." It is useless, of course, to deny that a largely seat-of-the-pants approach to studying fossils had served paleontologists well since the early nineteenth century. An intuitive appreciation of anatomical similarities and how they are distributed among living organisms had permitted some very smart people to arrive at a remarkably detailed and accurate description of the diversity of life. But even as I was receiving my rather dusty answer to my innocent question, I felt that surely there must be something more than this in the study of mute fossils.

And, of course, there is. Good fortune took me at the beginning of the 1970s to the American Museum of Natural History where a revolution in systematics (the science of analyzing relationships among organisms) was getting underway. This was the introduction into American systematics of "cladistic" methods (from the Greek word, *clados*, for "branch"). Traditionally, the paleoanthropological notion of theoretical rigor was to look at the "total morphological pattern" rather than at single characters in deciphering evolutionary relationships. The problem was, of course, that nobody could agree on what total morphological patterns actually were, so competing notions of relationship were impossible to test. Cladistics, in contrast, focuses on individual characters and recognizes the significance of the distinction between "primitive" and "derived" character states. For whereas common possession of primitive character states (those present in the ancestor of the group) indicates overall group membership, relationships *within* the group are only specified by the common possession of derived character states. These relationships are represented in branching diagrams called "cladograms". I will spare you the details of how primitive vs derived characters are recognized and how cladograms are constructed; suffice it to say that, with the advent of cladistics, systematics had finally acquired a truly scientific basis. For the statement "A and B possess derived characters not shared with C", which is what your simplest cladogram says, is truly testable, as is the inference that A and B are most closely related by common ancestry. With this approach in our toolkit, we can proceed to construct a firmly testable framework on which to hang our other hypotheses about the evolutionary histories of the groups we are interested in.

Of course, if we go beyond this to more complex (and admittedly more interesting) statements, for example, to hypotheses of ancestry and descent, the picture becomes murkier because such notions cannot be tested; we are back to probability judgements, and unquantifiable ones at that, although now we can see where they are coming from. The narrow-minded might conclude from this that science should stop right there; that when we move away from the strictly testable, we are moving beyond the boundaries of science. But of course, there is no reason whatever why scientists should not investigate the murkier and more intractable (not to mention more interesting) areas of human experience—and every reason why they should!

Science and Paleoanthropology

The science of paleoanthropology is a case in point. A full understanding of the lives of our early precursors goes well beyond knowing to whom they were most closely related. And filling in this story is precisely what was going on at Olduvai where we began this discussion. Some of those tiny figures down there on the Gorge's hot floor might have been paleontologists, looking for direct bony evidence of early humans and the animals they lived among. Others were probably archaeologists, looking for traces of early human activities (and indeed, it was at Olduvai that truly ancient stone tools were identified for the first time). Some may have been geologists, refining their ideas about what the rocks exposed in the Gorge's walls are telling us about past conditions. And yet others might have been taphonomists, scientists who try to elucidate what happens to animals after they die, and thus to understand exactly how the fragmentary evidence of the past has come down to us today. It is very important to know this, for not everything we observe can be taken at face value.

At one time, for example, it was believed that a 1.8-million-year-old circle of stones that had been noticed at a site on the Gorge's floor represented the remains of a deliberately constructed windbreak. If so, this was the earliest structure known, antedating anything comparable by well over a million years. Closer examination—testing of this hypothesis—showed, however, that the "stone circle" was almost certainly the result of shattering and scattering of stones by the roots of a growing tree. In retrospect, this was an early shot in a battle to revise, radically, our perspective on the nature of early hominids. At one time, these were widely viewed as little more than primitive, unsophisticated versions of *Homo sapiens*. Today, however, it is widely recognized that looking at our predecessors as junior league versions of ourselves may be profoundly misleading as a guide to understanding the kinds of creatures they were: another example, if on a very small scale, of paradigm change.

And hence, the very simple answer to the question with which we started this essay: What do all those very diverse folks down there in the Gorge have in common? Whatever their precise interests and techniques, they are all engaged in the attempt to expand, refine, and above all to test what we *think* we know about the past: an exercise that will ensure that this and other fields of scientific investigation will continue to evolve as long as there are scientists.