The Paradox of the Visibly Irrelevant

STEPHEN JAY GOULD

Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts 02138, USA

An odd principle of human psychology, well known and exploited by the full panoply of prevaricators, from charming barkers like Barnum to evil demagogues like Goebbels, holds that even the silliest of lies can win credibility by constant repetition. In current American parlance, these proclamations of "truth" by xeroxing fall into the fascinating domain of "urban legends."

My favorite bit of nonsense in this category intrudes upon me daily, and in very large type, thanks to a current billboard ad campaign by a company that will remain nameless. The latest version proclaims: "Scientists say we use 10% of our brains. That's way too much." Just about everyone regards the "truth" of this proclamation as obvious and incontrovertible—though you might still start a barroom fight over whether the correct figure should be 10, 15, or 20% (I have heard all three asserted with utter confidence). But this particular legend can only be judged as even worse than false: for the statement is truly meaningless and nonsensical. What do we mean by "90% unused"? What is all this superfluous tissue doing? The claim, in any case, can have no meaning until we develop an adequate theory about how the brain works. For now, we don't even have a satisfactory account for the neurological basis of memory and its storage—surely the *sine qua non* for formulating any sensible notion about unused percentages of brain matter! (I think that the legend developed because we rightly sense that we ought to be behaving with far more intelligence than we seem willing to muster—and the pseudoquantification of the urban legend acts as a falsely rigorous version of this legitimate, but vague, feeling.)

In my field of evolutionary biology, the most prominent urban legend—another "truth" known by "everyone"—holds that evolution may well be the way of the world, but one has to accept the idea with a dose of faith because the process occurs far too slowly to yield any observable result in a human lifetime. Thus, we can document evolution from the fossil record and infer the process from the taxonomic relationship of living species, but we cannot see evolution on human timescales "in the wild."

In fairness, we professionals must shoulder some blame for this utterly false impression about evolution's invisibility in the here and now of everyday human life. Darwin himself—though he knew and emphasized many cases of substantial change in human time (including the development of breeds in his beloved pigeons)—tended to wax eloquent about the inexorable and stately slowness of natural evolution. In a famous passage from the *Origin of Species*, he even devised a striking metaphor about clocks to underscore the usual invisibility:

> It may be said that natural selection is daily and hourly scrutinizing, throughout the world, every variation, even the slightest; rejecting that which is bad, preserving and adding up all that is good; silently and invisibly working .... We see nothing of these slow changes in progress until the hand of time has marked the long lapse of ages.

Nonetheless, the claim that evolution must be too slow to see can only rank as an urban legend—though not a completely harmless tale in this case, for our creationist incubi can then use the fallacy as an argument against evolution at any scale, and many folks take them seriously because they just "know" that evolution can never be seen in the immediate here and now. In fact, a precisely opposite situation actually prevails: biologists have documented a veritable glut of cases for rapid and eminently measurable evolution on timescales of years and decades.

However, this plethora of documents—while important for itself, and surely valid as a general confirmation for the proposition that organisms evolve—teaches us rather little about rates and patterns of evolution at the geological scales that build the history and taxonomic structure of life. The situation is wonderfully ironic, a point that I have tired to capture in the title of this article. The urban legend holds that evolution is too slow to document in palpable human lifetimes. The opposite truth has affirmed innumerable cases of measurable evolution at this minimal scale—but, to be visible at all over so short a span, evolution must be far too rapid (and transient) to serve as the basis for major transformations in geological time. Hence, the "paradox of the visibly irrelevant"—or, "if you can see it at all, it's too fast to matter in the long run!"

Our best and most numerous cases have been documented for the dominant and most evolutionarily active organisms on our planet—bacteria. In the most impressive of recent examples, Richard E. Lenski and Michael Travisano[1] monitored evolutionary change for 10,000 generations in 12 laboratory populations of the common human gut bacterium, *Escherichia coli*. By placing all 12 populations in identical environments, they could study evolution under ideal experimental conditions of replication, a rarity for the complex and unique events of evolutionary transformation in nature. In a fascinating set of results, they found that each population reacted and changed differently, even within an environment made as identical as human observers know how to do. Yet, Lenski and Travisano did observe some important and repeated patterns within the diversity. For example, each population increased rapidly in average cell size for the first 2000 generations or so, but then remained nearly stable for the last 5000 generations.

But a cynic might still reply: fine, I'll grant you substantial observable evolution in the frenzied little world of bacteria, where enormous populations and new generations every hour allow you to monitor 10,000 episodes of natural selection in a manageable time. But a similar "experiment" would consume thousands of years for multicellular organisms that measure generations in years or decades rather than minutes or hours. So we may still maintain that evolution cannot be observed in the big, fat, furry, sexually reproducing organisms that serve as the prototype for "life" in ordinary human consciousness. (A reverse cynic would then rereply that bacteria truly dominate life, and that vertebrates only represent a late-coming side-issue in the full story of evolution, however falsely promoted to centrality by our own parochial focus. But we must leave this deep issue to another time.)

I dedicate this essay to illustrating our cynic's error. Bacteria may provide our best and most consistent cases for obvious reasons, but measurable (and substantial) evolution has also, and often, been documented in vertebrates and other complex multicellular organisms. The classic cases have not exactly been hiding their light under a bushel, so I do wonder why the urban legend of evolution's invisibility persists with such strength. Perhaps the firmest and most elegant examples involve a group of organisms named to commemorate our standard bearer himself—Darwin's finches of the Galapagos Islands, where my colleagues Peter and Rosemary Grant have spent many years documenting fine-scale evolution in such adaptively important features as size and strength of the bill (a key to the mechanics of feeding), as rapid climatic changes force an alteration of food preferences. this work formed the basis for Jonathan Weiner's excellent book *The Beak of the Finch*, so the story has certainly been well and prominently reported in both the technical and popular press.

Nonetheless, new cases of such short-term evolution still maintain enormous and surprising power to attract public attention—for interesting and instructive, but utterly invalid, reasons as I shall show. I devote this essay to the three most prominent examples of recent publications that received widespread attention in the popular press as well. (One derives from my own research, so at least I can't be accused of sour grapes in the debunking that will follow, though I trust that readers will also grasp the highly positive twist that I will ultimately impose upon my criticisms.) I shall briefly describe each case, then present my two general critiques of their prominent reporting by the popular press, and finally explain why such cases teach us so little about evolution in the large, yet remain so important for themselves, and at their own equally legitimate scale.

GUPPIES FROM TRINIDAD

In many drainage systems on the island of Trinidad, populations of guppies live in downstream pools, where several species of fish can feed upon them. "Some of these species prey preferentially on large, mature-size classes of guppies." (I take all quotes from the primary technical article by Reznick *et al*.[2] that inspired later press accounts. Other populations of the same species live in "upstream portions of each drainage" where most "predators are excluded … by rapids or waterfalls, yielding low-predation communities."

In studying both kinds of populations, Reznick and colleagues found that "guppies from high-predation sites experience significantly higher mortality rates than those from low-predation sites." They then reared both kinds of guppies under uniform conditions in the laboratory and found that fishes from high-predation sites in lower drainages matured earlier and at a smaller size. "They also devote more resources to each litter, produce more, smaller offspring per litter and produce litters more frequently than guppies from low-predation localities."

This combination of observation from nature and the laboratory yields two important inferences. First, the differences make adaptive sense, for guppies subjected to greater predation would fare better if they could grow up fast and reproduce both copiously and quickly before the potential boom falls—a piscine equivalent of the old motto for electoral politics in Boston: vote early and vote often. On the other hand, guppies in little danger of being eaten might do better to bide their time and grow big and strong before engaging their fellows in any reproductive competition. Second, because these differences persist when both kinds of guppies are reared in identical laboratory environments, the distinction must record genetically based and inherited results of divergent evolution between the populations.

In 1981, Reznick had transferred some guppies from high-predation downstream pools into low-predation upstream waters then devoid of guppies. These transplanted populations evolved rapidly to adopt the reproductive strategy favored by indigenous populations in neighboring upstream environments: delayed sexual maturity at larger size and longer life. Moreover, Reznick and colleagues made the interesting observation that males evolved considerably more rapidly in this favored direction. In one experiment, males reached their full extent of change within 4 years, while females continued to alter after 11 years. Because the laboratory populations had shown higher heritability for these traits in males than in females, these results make good sense. (Heritability may be roughly defined as the correlation between traits in parents and offspring due to genetic differences. The greater the heritable basis of a trait, the faster the feature can evolve by natural selection.)

This favorable set of circumstances—rapid evolution in a predictable and presumably adaptive direction based on traits known to be highly heritable—provides a "tight" case for well-documented (and sensible) evolution at scales well within the purview of human observation, a mere decade in this case. The headline for the news report on this paper in *Science* magazine (March 28, 1997) read: "Predator-free guppies take evolutionary leap forward."

LIZARDS FROM THE EXUMA CAYS, BAHAMA ISLANDS

During most of my career, my field work has centered on the biology and paleontology of the land snail *Cerion* in the Bahama islands. During these trips, I have often encountered fellow biologists devoted to other creatures. In one major program of research, Tom Schoener (a biology professor at the University of California, Davis) has, with numerous students and colleagues, been studying the biogeography and evolution of the ubiquitous little lizard, *Anolis*—for me just a fleeting shadow running across a snail-studded ground, but for them a focus of utmost fascination (while my beloved snails, I assume, just blend into their immobile background).

In 1977 and 1981, Schoener and colleagues transplanted groups of 5 or 10 lizards from Staniel Cay in the Exuma chain to 14 small and neighboring islands that housed no lizards. In 1991, they found that the lizards had thrived (or at least survived and bred) on most of these islands, and they collected samples of adult males from each experimental island with an adequate population. In addition, they gathered a larger sample of males from areas on Staniel Cay that had served as the source for original transplantation in 1977 and 1981.

This study then benefits from general principles learned by extensive research on numerous *Anolis* species throughout the Bahama islands. In particular, relatively longer limbs permit greater speed, a substantial advantage provided that preferred perching places can accommodate long-legged lizards. Trees, and other "thick" perching places therefore favor the evolution of long legs. Staniel Cay itself includes a predominant forest, and the local *Anolis* tend to be long legged. But when lizards must live on thin twigs in bushy vegetation, the agility provided by shorter legs (on such precarious perches) may outweigh the advantages in speed that longer legs would provide. Thus, lizards living on narrow twigs tend to be shorter-legged. The small Cays that received the 14 transported populations have little or no forest growth and tend instead to be covered with bushy vegetation (and narrow twigs).

J.B. Losos, the principal author of the new study, therefore based an obvious prediction on these generalities. The populations had been transferred from forests with wide perches to bushy islands covered with narrow twigs. “From the kind of vegetation on the new islands,” Losos stated, “we predicted that the lizards would develop shorter hindlimbs.” Their published study validates this expected result: a clearly measurable change, in the predicted and adaptive direction, in less than 20 years.[3] A news report appeared in *Science* magazine (May 2, 1997) under the title: “Catching lizards in the act of adapting.”

This study lacks a crucial piece of documentation that the Trinidadian guppies provided, an absence immediately noted by friendly critics and fully acknowledged by the authors. Losos and colleagues have not studied the heritability of leg length in *Anolis sagrei*, and therefore cannot be certain that their results record a genetic process of evolutionary change. The growth of these lizards may feature extensive flexibility in leg length, so that the same genes yield longer legs if lizards grow up on trees and shorter legs if they always cavort in the bushes (just as the same genes can lead to a thin or fat human being depending upon a personal history of nutrition and exercise). In any case, however, a sensible and apparently adaptive change in average leg length has occurred within 20 years on several islands, whatever the cause of modification.

SNAILS FROM GREAT INAGUA, BAHAMA ISLANDS

Most of Great Inagua, the second largest Bahamian Island (Andros wins first prize), houses a large and ribby *Cerion* species named *C. rubicundum*. But fossil deposits of no great age lack this species entirely and feature instead an extinct form named *Cerion excelsior*, the largest of all *Cerion* species. Several years ago, on a mudflat in the southeastern corner of Great Inagua, David Woodruff (of the University of California, San Diego) and I collected a remarkable series of shells that seemed to span (and quite smoothly) the entire range of form from extinct *C. excelsior* to modern *C. rubicundum.* Moreover, and in general, the more eroded and “older looking” the shell, the closer it seemed to lie to the anatomy of extinct *C. excelsior.*

This situation suggested a local evolutionary transition by hybridization, as *C. rubicundum*, arriving on the island from an outside source, interbred with indigenous *C. excelsior*. Then, as *C. excelsior* declined towards extinction while *C. rubicundum* thrived and increased, the average anatomy of the population transformed slowly and steadily in the direction of the modern form; this hypothesis sounded good and sensible, but we could devise no way to test our idea, because all the shells had been collected from a single mud flat (analogous to a single bedding plane of a geological stratum), and we could not determine their relative ages. The pure *C. excelsior* shells “looked” older, but such personal impressions count for less than nothing (subject as they are to a researcher’s bias) in science. So we got stymied and put the specimens in a drawer.

Several years later, I teamed up with paleontologist and geochemist Glenn A. Goodfriend from the Carnegie Institution of Washington. He had refined a dating technique based on changes in the composition of amino acids in the shell over time. By keying these amino acids changes to radiocarbon dates for some of the shells, we could estimate the age of each shell. A plot of shell age versus position on an anatomical spectrum from extinct *C. excelsior* to modern *C. rubicundum* produced a beautiful correlation between age and anatomy: the younger the specimen, the closer to the modern anatomy.

This ten to twenty thousand year transition by hybridization exceeds the time period of the Trinidad and Exuma studies by three orders of magnitude (that is, by a factor of 1000), but even 10,000 years represents a geological eye-blink in the fullness of evolutionary time; whereas this transformation in our snails marks a full change from one species to another, not just a small decrement of leg length or a change in the timing of breeding within a single species. (For details, see G.A. Goodfriend and S.J. Gould.[4]) Harvard University's release (with no input from me) carried the headline: "snails caught in act of evolving."

A scanning of any year's technical literature in evolutionary biology would yield numerous and well-documented cases of such measurable, small-scale evolutionary change, thus disproving the urban legend that evolution must always be too slow to observe in the geological microsecond of a human lifetime. These three studies, all unusually complete in their documentation and in their resolution of details, do not really rank as "news" in the journalist's prime sense of novelty or deep surprise. Nonetheless, each of these three studies became subjects for front page stories in either the *New York Times* or *Boston Globe*.

Now please don't get me wrong. I do not belong to the cadre of rarefied academics who cringe at every journalistic story about science for fear that the work reported might become tainted with popularity thereby. And, in a purely "political" sense, I certainly won't object if major newspapers choose to feature any result of my profession as a lead story—especially, if I may be self-serving for a moment, when one of the tales reports my own work! Nonetheless, this degree of public attention for workaday results in my field (however elegantly done), does fill me with wry amusement, if only for the general reason that most of us feel a tickle in the funny bone when we note a gross imbalance between public notoriety and the true novelty or importance of an event, as when Hollywood spinmeisters manage to depict their client's ninth marriage as the earth's example of true love triumphant and permanent.

Of course I'm delighted that some ordinary, albeit particularly well done, studies of small scale evolution struck journalists as front page news. But I still feel impelled to ask why these studies, rather than 100 others of equal care and merit that appear in our literature every month, caught this journalistic fancy and inspired such prime attention. When I muse over this issue, I can only devise two reasons, both based on deep and interesting fallacies well worth identifying and discussing. In this sense, the miselevation of everyday good work to surprising novelty may teach us something important about public attitude towards evolution, and towards science in general. We may, I think, resolve each of the two fallacies by contrasting the supposed meaning of these studies, as reported in public accounts, with the significance of such work as viewed by professionals in the field.

THE FALLACY OF THE CRUCIAL EXPERIMENT

In high school physics classes, we all learned a heroically simplified version of scientific progress based on a model that does work sometimes, but by no means always: the *experimentum crucis*, or crucial experiment. Newton or Einstein? Ptolemy or Copernicus? Special Creation or Darwin? To find out, perform a single, decisive experiment with a clearly measurable result replete with decisive power to decree yea or nay.

The decision to treat a limited and particular case as front page news must be rooted in this fallacy. Reporters must imagine that evolution can be proved by a single crucial case, so that any of these stories may provide decisive confirmation of Darwin's truth—a matter of some importance given the urban legend that evolution, even if valid, must be invisible on human timescales.

But two counterarguments vitiate this premise. First, as a scientific or intellectual issue, we hardly need to "prove" evolution by discovering new and elegant cases. We do not, after all, expect to encounter a page-one story with the headline "new experiment proves earth goes around sun, not vice versa. Galileo vindicated." The fact of evolution has been equally well documented for more than a century.

Second, and more generally, single "crucial" experiments rarely decide major issues in science, especially in natural history where nearly all theories require data about "relative frequencies" (or percentage of occurrences), not pristine single cases. Of course, for a person who believes that evolution never occurs at all, one good case can pack enormous punch, but science resolved this basic issue more then one hundred years ago. Nearly every interesting question in evolutionary theory asks "how often" or "how dominant in setting the pattern of life"—not "does this phenomenon occur at all?" For example, on the most important issue of all—the role of Darwin's own favored mechanism of natural selection—single examples of selection's efficacy advance the argument very little. We already know, by abundant documentation and rigorous theorizing, that natural selection can and does operate in nature. We need to determine the *relative strength* of Darwin's mechanism among a set of alternative modes for evolutionary change; and single cases, however elegant, cannot establish a relative frequency.

Professionals also commit this common error of confusing well-documented single instances with statements about relative strength among plausible alternatives. For example, we would like to know how often small and isolated populations evolve differences as adaptive responses to local environments (presumably by Darwin's mechanism of natural selection), and how often such changes occur by the random process known as "genetic drift," a potentially potent phenomenon in small populations (just as a small number of coin flips can depart radically from 50–50 for heads and tails, while a million flips with an honest coin cannot stray too far from this ideal). Losos's study on lizard legs provides one vote for selection (if the change turns out to have a genetic basis), because leg length altered in a predicted direction towards better adaptation to local environments on new islands. But even such an elegant case cannot prove the domination of natural selection in general. Losos has only shown the power of Darwin's process in a particular example. Yet the reporter for *Science* magazine made this distressingly common error in concluding: "If it [change in leg length] is rooted in the genes, then the study is strong evidence that isolated populations diverge by natural selection, not genetic drift as some theorists have argued." Yes, strong evidence for these lizards on that island during those years—but not proof for the general domination of selection over drift. Single cases don't establish generalities, so long as alternative mechanisms retain their theoretical plausibility.

THE PARADOX OF THE VISIBLY IRRELEVANT

As a second reason for overstating the centrality of such cases in our general understanding of evolution, many commentators (and research scientists as well) ally themselves too strongly with one of the oldest (and often fallacious) traditions of Western thought: reductionism, or the assumption that laws and mechanics of the smallest constituents must explain objects and events at all scales and times. Thus, if we can render the behavior of a large body (an organism or a plant, for example) as a consequence of atoms and molecules in motion, we feel that we have developed a "deeper," or "more basic" understanding than if our explanatory principles engage only large objects themselves and not their constituent parts.

Reductionists assume that documenting evolution at the smallest scale of a few years and generations should provide a general model of explanation for events at all scales and times—so these cases should become a gold standard for the entire field, hence their status as front-page news. The authors of our two studies on decadal evolution certainly nurture such a hope. Reznick and colleagues end their publication on Trinidadian guppies by writing: "It is part of a growing body of evidence that the rate and patterns of change attainable through natural selection are sufficient to account for the patterns observed in the fossil record." Losos and colleagues say much the same for their lizards "Macroevolution may just be microevolution writ large—and, consequently, insight into the former may result from study of the latter."

We tend to become beguiled by such warm and integrative feelings (for science rightly seeks unity and generality of explanation). But does integration by reduction of all scales to the rates and mechanisms of the smallest really work for evolution, and do we crave this style of unification as the goal of all science? I think not, and I also regard our best general reason for skepticism as conclusive for this particular subject, however rarely appreciated though staring us in the face.

These shortest term studies are elegant and important, but they cannot represent the general mode for building patterns in the history of life. The reason for their large-scale impotence strikes most people as deeply paradoxical, even quite funny, but the argument truly cannot be gainsaid. Evolutionary rates as measured for guppies and lizards, are *vastly too rapid* to represent the general modes of change that build life's history through geological ages. But how can I say such a thing? Isn't this statement ridiculous *a priori*? How could these tiny, minuscule changes—a little less leg, a minimally larger size—represent too much of anything? Doesn't the very beauty of these studies lie in their minimalism? We have always been taught that evolution is wondrously slow and cumulative, a grain by grain process, a penny a day towards the domain of Bill Gates. Doesn't each of these studies document a grain? Haven't my colleagues and I found the "atom" of evolutionary incrementation?

I believe that these studies have discerned something important, but they have discovered no general atom. These measured changes over years and decades are too fast by several orders of magnitude to build the history of life by simple cumulation. Reznick's guppy rates range from 3700 to 45,000 darwins (a standard metric for evolution, expressed as change in units of standard deviation—a measure of variation around the mean value of a trait in a population—per million years). By contrast, rates for major trends in the fossil record generally range from 0.1 to 1.0 darwins. Reznick himself states that "the estimated rates [for guppies] are … four to seven orders of magnitude greater than those observed in the fossil record" (that is, ten thousand to ten million times faster?).

Moreover and with complete generality, thus constituting the "paradox of the visibly irrelevant" in my title, we may say that any change measurable *at all* over the few years of an ordinary scientific study must be occurring far too rapidly to represent ordinary rates of evolution in the fossil record. The culprit of this paradox, as so often, can be identified as the vastness of time (a concept that we can appreciate "in our heads" but seem quite unable to place into the guts of our intuition). The key principle, however ironic, requires such a visceral understanding of earthly time: if a case of evolution proceeds with sufficient speed to be discerned by our instruments in just a few years—that is, if the change becomes substantial enough to stand out as a genuine and directional effect above the random fluctuations of nature's stable variation and our inevitable errors of measurement—then we have witnessed something far too substantial to serve as an atom of steady incrementation in a paleontological trend. Thus, to restate the paradox: if we can measure it at all (in a few years), it is too powerful to be the stuff of life's history.

If large scale evolution proceeded by stacking Trinidad guppy rates end to end, then any evolutionary trend would be completed in a geological moment, not over the many million years actually observed. "Our face from fish to man," to cite the title of a famous old account of evolution for popular audiences, would run its course within a single geological formation, not over more than 400 million years, as our fossil record demonstrates.

Evolutionary theory must figure out how to slow down these measured rates of the moment, not how to stack them up! In fact, most lineages are stable (*non*-changing) nearly all the time in the fossil record. When lineages do change, their alteration usually occurs "momentarily" in a geological sense (that is, confined to a single bedding plane) and usually leads to the origin of a new species by branching. Evolutionary rates during these moments may match the observed speed of Trinidadian guppies and Bahamian lizards, because most bedding planes represent several thousand years. But, during most of a typical species' lifetime, no change accumulates, and we need to understand why. The sources of stasis have become as important for evolutionary theory as the causes of change.

(To illustrate how poorly we grasp this central point about time's immensity, the reporter for *Science* magazine called me when my *Cerion* article, co-authored with Glenn Goodfriend, appeared. He wanted to write an accompanying news story about the exception I had found to own theory of punctuated equilibrium, an insensibly gradual change over 10 to 20 thousand years. I told him that, although exceptions abound, this case does not lie among them, but actually represents a strong confirmation of punctuated equilibrium! We found all 20,000 years worth of snails on a single mud flat, that is, on what would become a single bedding plane in the geological record. Our *entire* transition occurred in a geological moment and represented a punctuation, not a gradual sequence of fossils. We were able to "dissect" the punctuation in this unusual case, hence the value of our publication, because we could determine ages for the individual shells. The reporter, to his credit, completely revised his originally intended theme, and published an excellent account.)

In conclusion, I suspect that most cases like the Trinidadian guppies and Bahamian lizards represent transient and momentary blips and fillips that "flesh out" the rich history of lineages in stasis, not the atoms of substantial and steadily accumulated evolutionary trends. Stasis is a dynamic phenomenon. Small local populations and parts of lineages make short and temporary forays of transient adaptation, but these tiny units almost always die out or get reintegrated into the general pool of the species. (Losos himself regards the new island populations of lizards as evolutionarily transient in exactly this sense, because for such tiny and temporary colonies are almost always extirpated by hurricanes in the long run. How, then, can such populations represent atoms of a major evolutionary trend? The news report in *Science* magazine ends by stating: “But whether the lizards continue to evolve depends largely on the winds of fate, says Losos. These islet are periodically swept by hurricanes that could whisk away every trace of anolian evolution.”)

But transient blips and fillips are no less important than major trends in the total “scheme of things.” Both represent evolution operating at a standard and appropriate measure for a particular scale and time—Trinidadian blips for the smallest and the most local moment, faces from fish to human for the largest and the most global frame. One scale doesn’t translate into another. No single scale can be deemed more important than any other, and none operates as a basic model for all the others. Each scale embodies something precious and unique to teach us; none can be labeled superior or primary. (Guppies and lizards, in their exposition of momentary detail, give us insight, unobtainable at broader scales, into the actual mechanics of adaptation, natural selection, and genetic change.)

The common metaphor of the science of fractal models—Mandelbrot’s familiar argument that the coast of Maine has no absolute length, but depends upon the scale of measurement—epitomizes this principle well. When we study guppies in a pond in Trinidad, we are operating at a scale equivalent to measuring the coastline by wrapping our string around every boulder on every headland of Acadia National Park. When we trace the increase in size of the human brain from Lucy (about 4 million years ago) to Lincoln, we are measuring the coastline as depicted on my page of Maine in Hammond’s Atlas. Both scales are exactly right for their appropriate problems. You would be a fool to spend all summer measuring the details in one cove in Acadia, if you just wanted to know the distance from Portland to Machiasport for your weekend auto trip.

I find a particular intellectual beauty in such fractal models—for they invoke hierarchies of inclusion (the single cove embedded within Acadia, embedded within Maine) to deny hierarchies of worth, importance, merit, or meaning. You may ignore Maine while studying the sand grain and be properly oblivious of the grain while perusing the single-page map of Maine on the single pages of your atlas. But you can love and learn from both scales at the same time. Evolution does not lie patent in a clear pond on Trinidad any more than the universe (*pace* Mr. Blake) lies revealed in a grain of sand. But how poor would be our understanding, how bland and restricted our sight, if we could not learn to appreciate the rococo details that fill our immediate field of vision, while forming, at another scale, only some irrelevant and invisible jigglings in the majesty of geological time.

REFERENCES

1. Lenski, Richard E. & Michael Travisano. 1994. Proc. Natl. Acad. Sci. USA **91:** 6808–6814.

2. Reznick, D.N., F.H. Shaw, F.H. Rodd & R.G. Shaw. 1977. Evaluation of the rate of evolution in natural populations of guppies (*Poecilia reticulata*). Science **275:** 1934–1937.
3. Losos, J.B., K.I. Warheit & T.W. Schoener. 1997. Adaptive differentiation following experimental island colonization in Anolis lizards. Nature **387:** 70–73.
4. Goodfriend, G.A. & S.J. Gould. 1996. Paleontology and chronology of two evolutionary transitions by hybridization in the Bahamian land snail *Cerion*. Science **274:** 1894–1897.