

## The scientific pretensions of atheism

The enclosed anthology of articles (mainly from *Commentary*) by mathematician David Berlinski, summarizes the substantial scientific deficiencies in current attempts to explain the origin of the universe (cosmic evolution), the origin of life (chemical evolution) and the development of life (biological evolution). Few readers are aware of the grave objections to these theories that attempt to explain the marvels of life via the combination of unguided naturalistic processes and chance without reference to intelligent agency.

The blurb to Berlinski book *The Devil's Delusion: Atheism and Its Scientific Pretensions* (Crown Forum, 2008) states: Militant atheism is on the rise. Richard Dawkins, Sam Harris, Daniel Dennett, and Christopher Hitchens have dominated bestseller lists with books denigrating religious belief as dangerous foolishness. And these authors are merely the leading edge of a far larger movement—one that now includes much of the scientific community. “The attack on traditional religious thought,” writes David Berlinski in *The Devil’s Delusion*, “marks the consolidation in our time of science as the single system of belief in which rational men and women might place their faith, and if not their faith, then certainly their devotion.” A secular Jew, Berlinski nonetheless delivers a biting defense of religious thought. An acclaimed author who has spent his career writing about mathematics and the sciences, he turns the scientific community’s cherished skepticism back on itself, daring to ask and answer some rather embarrassing questions:

Has anyone provided a proof of God’s inexistence? *Not even close.*

Has quantum cosmology explained the emergence of the universe or why it is here? *Not even close.*

Have the sciences explained why our universe seems to be fine-tuned to allow for the existence of life?  
*Not even close.*

Are physicists and biologists willing to believe in anything so long as it is not religious thought? *Close enough.*

Has rationalism in moral thought provided us with an understanding of what is good, what is right, and what is moral? *Not close enough.*

Has secularism in the terrible twentieth century been a force for good? *Not even close to being close.*

Is there a narrow and oppressive orthodoxy of thought and opinion within the sciences? *Close enough.*

Does anything in the sciences or in their philosophy justify the claim that religious belief is irrational?  
*Not even ballpark.*

Is scientific atheism a frivolous exercise in intellectual contempt? *Dead on.*

Berlinski does not dismiss the achievements of western science. The great physical theories, he observes, are among the treasures of the human race. But they do nothing to answer the questions that religion asks, and they fail to offer a coherent description of the cosmos or the methods by which it might be investigated.

# Darwinian Doubts

By DAVID BERLINSKI

The defense of Darwin's theory of evolution has now fallen into the hands of biologists who believe in suppressing criticism when possible and ignoring it when not. It is not a strategy calculated to induce confidence in the scientific method.

A paper published recently in the Proceedings of the Biological Society of Washington concluded that the events taking place during the Cambrian era could best be understood in terms of an intelligent design — hardly a position unknown in the history of western science. The paper was, of course, peer-reviewed by three prominent evolutionary biologists. Wise men attend to the publication of every one of the Proceeding's papers, but in the case of Steven Meyer's "The origin of biological information and the higher taxonomic categories," the Board of Editors was at once given to understand that they had done a bad thing. Their indecent capitulation followed at once. Publication of the paper, they confessed, was a mistake. It would never happen again. It had barely happened at all. And peer review?

The hell with it.

"If scientists do not oppose anti-evolutionism," Eugenie Scott, the executive director of the National Council on Science Education, remarked, "it will reach more people with the mistaken idea that evolution is scientifically weak." Scott's understanding of "opposition" had nothing to do with reasoned discussion. It had nothing to do with reason at all. Discussing the issue was out of the question. Her advice to her colleagues was considerably more to the point: "Avoid debates."

Everyone else had better shut up.

In this country, at least, no one is ever going to shut up, the more so since the case against Darwin's theory retains an almost lunatic vitality.

*Look* — The suggestion that Darwin's theory of evolution is like theories in the serious sciences — quantum electrodynamics, say — is grotesque. Quantum electrodynamics is accurate to 13 unyielding decimal places. Darwin's theory makes no tight quantitative predictions at all.

*Look* — Field studies attempting to measure natural selection inevitably report weak to non-existent selection effects.

*Look* — Darwin's theory is open at one end since there are no plausible accounts for the origins of life.

*Look* — The astonishing and irreducible complexity of various cellular structures has not yet successfully been described, let alone explained.

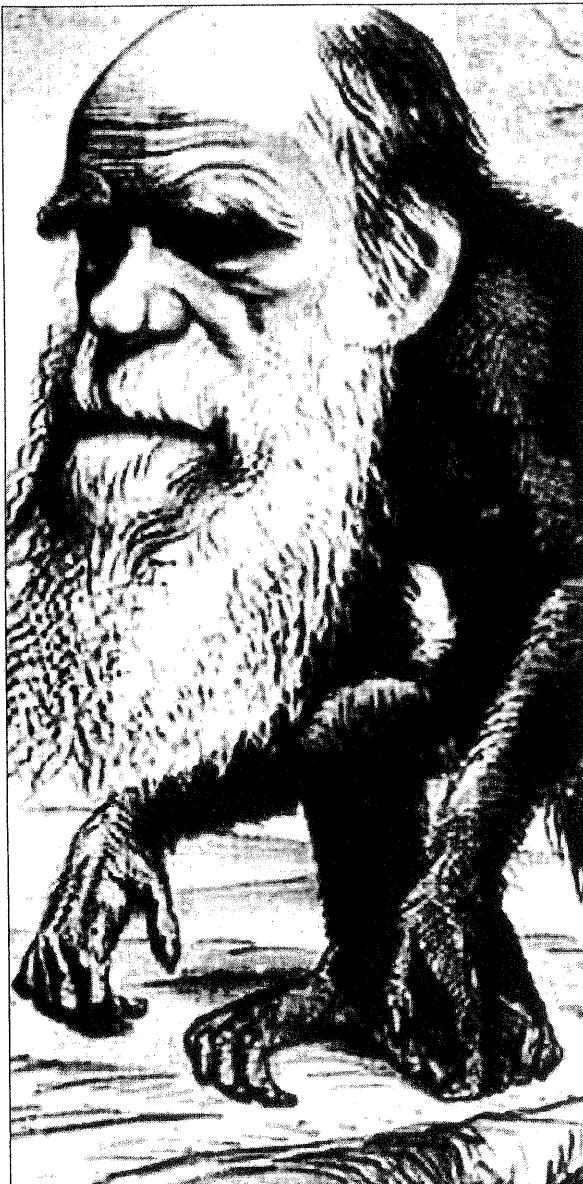
*Look* — A great many species enter the fossil record trailing no obvious ancestors and depart for Valhalla leaving no obvious descendants.

*Look* — Where attempts to replicate Darwinian evolution on the computer have been successful, they have not used classical Darwinian principles, and where they have used such principles, they have not been successful.

*Look* — Tens of thousands of fruit flies have come and gone in laboratory experiments, and every last one of them has remained a fruit fly to the end, all efforts to see the miracle of speciation unavailing.

*Look* — The remarkable similarity in the genome of a great many organisms suggests that there is at bottom only one living system; but how then to account for the astonishing differences between human beings and their near relatives — differences that remain obvious to anyone who has visited a zoo?

*But look again* — If the differences between organisms are scientifically more interesting than their genomic similarities, of what use is Darwin's theory since its otherwise mysterious operations take place by



genetic variations?

These are hardly trivial questions. Each suggests a dozen others. These are hardly circumstances that do much to support the view that there are "no valid criticisms of Darwin's theory," as so many recent editorials have suggested.

Serious biologists quite understand all this. They rather regard Darwin's theory as an elderly uncle invited to a family dinner. The old boy has no hair, he has no teeth, he is hard of hearing, and he often drools. Addressing even senior members at table as *Sonny*, he is inordinately eager to tell the same story over and over again.

But he's family. What can you do?

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# Commentary

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## Was There a Big Bang?

*David Berlinski*

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SCIENCE IS a congeries of great quests, and cosmology is the grandest of the great quests. Taking as its province the universe as a whole, cosmology addresses the old, the ineradicable questions about space and time, nature and destiny. It is not a subject for the tame or the timid.

For the first half of the 20th century, cosmology remained a discipline apart, as a clutch of talented but otherworldly physicists peeped inconclusively at a universe they could barely see: Albert Einstein, of course; the Dutch mathematician Willem de Sitter; the Belgian abbot Georges Lemaître; and the extraordinary Russian mathematician and meteorologist Aleksandr Friedmann, destined to die young, or so the story has it, from exposure to the elements suffered while soaring above Moscow in a weather balloon.

When in 1917 Einstein published his first estimates of the size and shape of the universe, telescopes could not penetrate the heavens beyond the Milky Way. Like a sailor endeavoring to measure the depth of the sea from the shore, astronomers lacked the means to probe the heavens further or to probe them in detail.

This has now changed. Information pours from the night skies, terrestrial telescopes hissing and clicking as they rotate to survey distant galaxies. Somewhere in space, the realigned Hubble telescope peers into the unpolluted depths. Physicists have pictures of the backside of beyond, and they appear to have overheard the cosmic cackle that accompanied the very crack of time, as nothingness gave way to light. The cosmologists have come into their own, handling the universe with an easy familiarity and writing book after book in which they explain in exuberant detail how the great things were done.

*The Great Cause*

**W**HATEVER THE dreams we dream, the existence of the universe has always seemed a riddle beyond reason, if only because our imagination is forever suspended between ideas of creation and timelessness. Many ancient myths depict the universe as the effect of some Great Cause. In the Babylonian epic *Enuma Elish*, existence is attributed to congress between "primordial Aspu, the Begetter" and "Mummu-Tiamet, she who bore them all." Although the connection cosmic and sexual energies is both familiar and disturbing, it is not congress between gods that is crucial to the myth but the idea that the universe came into being as the result of a Great Cause. And this idea is conveyed by the opening of Genesis as well: "In the beginning, God created the heavens and the earth."

These are words that express an authentically universal concept, one familiar to every culture. But while the concept of creation is common, it is also incoherent. "I venture to ask," the 3rd-century Chinese sage Kuo Hsiang ventured to ask, "whether the Creator is or is not. If He is not, how can He create things? And if He is, then (being one of these things) He is incapable (without self-creation) of creating the mass of bodily forms." That this argument is simple is no reason to think it wrong.

If not creation by a Great Cause, what, then, of timelessness: a universe proceeding sedately from everlasting to everlasting? In Maori myth, the world parents who bring the cosmos into being arise themselves from *po*, a kind of antecedent gruel or stuff, so that the universe appears as an episode in an infinitely extended drama. Some variant of this idea is also universal, a place in every culture where the weary mind takes refuge. Yet if timelessness offers an escape from the paradoxes of creation, the escape can easily seem an evasion. An everlasting universe is itself an object requiring explanation: if it is unprofitable to ask *when* it arose, one nonetheless wonders why the damn thing should be there at all.

It is the remarkable claim of contemporary cosmology to have broken, and broken decisively, the restless movement of the mind as it passes from theory to theory and from myth to myth. "Incomplete though it may be," one physicist has written, "the scope of modern scientific understanding of the cosmos is truly dazzling." This is not hyperbole. It is an assessment widely shared among physicists, and thus the standard by which their claims must be judged.

The universe, cosmologists now affirm, came into existence as the expression of an explosion, the cosmos shaking itself into existence from the bang of an initial singularity. It is tempting to think of the event in humanly comprehensible terms--a *gigantic* explosion or a *stupendous* eruption, as if, popcorn in hand, we were watching the show from far away. But this is absurd. The Big Bang was not an event taking place at a time or in a place. Space and time were themselves created by the Big Bang, the measure along with the measured.

As far as most physicists are concerned, the Big Bang is now a part of the structure of serene indubitability created by modern physics, an event undeniable as the volcanic explosion at Krakatoa. From time to time, it is true, the astrophysical journals report the

failure of observation to confirm the grand design. It hardly matters. The physicists have not only persuaded themselves of the merits of Big Bang cosmology, they have persuaded everyone else as well. The Big Bang has come to signify virtually a universal creed; men and women who know nothing of cosmology are convinced that the rumble of creation lies within reach of their collective memory.

### *The Cosmic Archeologist*

LOOKING AT a few shards of pottery on the desert floor, the archeologist is capable of conjuring up the hanging gardens of the past, the smell of myrrh and honey in the air. His is an act of intellectual reconstruction, one made poignant by the fact that the civilization from which the artifacts spring lies forever beyond the reach of anything but remembrance and the imagination. Cosmology on the grand scale is another form of archeology; the history of the cosmos reveals itself in layers, like the strata of an ancient city.

The world of human artifacts makes sense against the assumption of a continuous human culture. The universe is something else: an old, eerie place with no continuous culture available to enable us to make sense of what we see. It is the hypothesis that the universe is *expanding* that has given cosmologists a unique degree of confidence as they climb down the cliffs of time.

A universe that is expanding is a universe with a clear path into the past. If things are now far apart, they must at one point have been close together; and if things were once close together, they must at one point have been *hotter* than they are now, the contraction of space acting to compress its constituents like a vise, and so increase their energy. The retreat into the past ends at an initial singularity, a state in which material particles are at *no* distance from each other and the temperature, density, and curvature of the universe are infinite.

The cosmic archeologist may now be observed crawling back up the cliffs of time he so recently descended. During the first  $10^{-43}$  seconds after the Big Bang-- $10^{-43}$  is one over a ten followed by 42 zeros--both matter and radiation fill the void. A reign of fluid interchange obtains, with particles of matter and antimatter exchanging identities. As the primitive goo of the cosmos--what the physicist George Gamow called *ylem*, the primordial stuff--continues to expand, it continues to cool. Neutrinos, photons, electrons, positrons, neutrons, and protons agitate themselves throughout space. With the temperature dropping, the neutrinos decamp for parts unknown.

At roughly one-and-one-half seconds after the Big Bang, protons and neutrons lose the ability to exchange identities, and the ratio of neutrons to protons in the universe freezes itself at one to six. Three-and-one-half seconds later, the equilibrium between electrons and positrons collapses, and the positrons follow the neutrinos into the void.

Three minutes pass. The era of nucleosynthesis begins thereafter. Those neutrons that during the freeze-out found themselves bound to the world's vagrant protons now take up an identity as a form of helium. Other elements wait patiently for the stars to be born so that they may be cooked in their interiors.

The universe continues to expand, pulse, glow, throb, and moan for 400,000 years more, passing insensibly from a place where radiation predominates to an arena where matter has taken charge and is in command. The temperature is now 4,000 degrees Kelvin. The great era of *recombination* is at hand, a burst of cosmic creativity recorded in the walls of time. Free electrons and protons form hydrogen. The interaction between matter and radiation changes dramatically.

Until recombination, photons found themselves trapped within a cosmic pinball machine, ricocheting from one free charged particle to another, the cosmos frustratingly opaque because frustratingly dense. But hydrogen binds the cosmic debris, and for the first time, light streams from one side of creation to the other. The early universe fills with low-temperature blackbody radiation, the stuff destined to be observed fifteen billion years later in Princeton, New Jersey, as cosmic background radiation (CBR).

The separation of light and matter allows the galaxies to form, gravity binding the drifting dust in space. At last, the universe fills with matter, the stars settling into the sky, the far-flung suns radiating energy, the galaxies spreading themselves throughout the heavens. On the earth that has been newly made, living things shamble out of the warm oceans, the cosmic archeologist himself finally clambering over the lip of time to survey the scene and take notes on all that has occurred.

Such is the standard version of hot Big Bang cosmology--"hot" in contrast to scenarios in which the universe is cold, and "Big Bang" in contrast to various steady-state cosmologies in which nothing ever begins and nothing ever quite ends. It may seem that this archeological scenario leaves unanswered the question of *how* the show started and merely describes the consequences of some Great Cause that it cannot specify and does not comprehend. But really the question of how the show started answers itself: before the Big Bang there was nothing. *Darkness was upon the face of the deep.*

### *Blow-Up*

**N**O TWITHSTANDING THE investment made by the scientific community and the general public in contemporary cosmology, a suspicion lingers that matters do not sum up as they should. Cosmologists write as if they are quite certain of the Big Bang, yet, within the last decade, they have found it necessary to augment the standard view by means of various new theories. These schemes are meant to solve problems that cosmologists were never at pains to acknowledge, so that today they are somewhat in the position of a physician reporting both that his patient has not been ill and that he has been successfully revived.

The details are instructive. It is often said, for example, that the physicists Arno Penzias and Robert Wilson observed the remnants of the Big Bang when in 1962 they detected, by means of a hum in their equipment, a signal in the night sky they could not explain. This is not quite correct. What Penzias and Wilson *observed* was simply the same irritating and ineradicable noise that has been a feature of every electrical appliance I have ever owned. What theoreticians like Robert Dicke *inferred* was something else: a connection between that cackle and the cosmic background radiation released into the universe after the era of recombination.

The cosmic hum is real enough, and so, too, is the fact that the universe is bathed in background radiation. But the era of recombination is a shimmer by the doors of theory, something known indirectly and only by means of its effects. And therein lies a puzzle. Although Big Bang cosmology does predict that the universe should be bathed in a milky film of radiation, it makes no predictions about the uniformity of its temperature. Yet, looking at the sky in every direction, cosmologists have discovered that the CBR has the same temperature, to an accuracy of one part in 100,000.

Why should this be so? CBR filled the universe some 400,000 years after the Big Bang; if its temperature thereafter is utterly and entirely the same, some physical agency must have brought this about. But by the time of recombination, the Big Bang had blown up the universe to a diameter of 90,000,000 light years. A physical signal--a light beam, say--sent hustling into the cosmos at Time Zero would, a mere 400,000 years later, be hustling still; by far the greater part of the universe would be untouched by its radiance, and so uninfluenced by the news that it carried. Since, by Einstein's theory of special relativity, nothing can travel faster than light itself, it follows that no physical agency would have had time enough to establish the homogeneity of the CBR, which appears in Big Bang cosmology as an arbitrary feature of the early universe, something that must be assumed and is not explained.

**T**HEORIES OF *inflation* now make a useful appearance. Their animating idea represents a contribution to cosmology from particle physics--a rare example of intellectual lend-lease, and evidence that disciplines dealing with the smallest of objects may be relevant to disciplines dealing with the largest. Within what is now known as the Standard Model, the familiar arrangement in which elementary particles are moved by various forces gives way to a mathematically more general scheme in which fields replace both particles and forces as essential theoretical structures. A field is an expanse or expression of space, something like a surface in two dimensions, or the atmosphere in three, or space and time in four. The Standard Model in particle physics consists of a dozen or so fields, exchanging energy with one another and subsidizing particles by means of the energy they contain.

It is the Higgs field that originally came to play a novel role in Big Bang cosmology. Named after Peter Higgs, the Scottish physicist who charmed it into existence, the Higgs field is purely a conjectured object. Its cosmological potential was first noted by a young American physicist, Alan Guth.

Fields are structures that carry latent energy even under conditions in which the space they control is to all intents and purposes empty. The natural and stable state of the Higgs field is one in which its latent energy is at a minimum. Such is its true vacuum state, the word "vacuum" indicating that the field is empty, and the word "true" that the field is in its lowest energy configuration. But under certain physically possible circumstances, the Higgs field can find itself adventitiously trapped in a *false* vacuum state, a condition in which, like a spring, it is loaded with potential energy. It is thus, Guth conjectured, that the Higgs field might have found itself fluttering about the early universe, energetically throbbing and dying to be of use.

The wish is father to the act. The energy within the Higgs field is repulsive: it pushes things apart. When released, it contributes a massive jolt to the process of cosmic expansion already under way. The universe very quickly doubles in size. Space and time stretch themselves out. Particles zoom from one another. If the ordinary course of cosmic expansion is linear, inflationary expansion is exponential, like the gaunt, hollow-eyed guest gobbling the hors d'oeuvres--and everything else--at a previously decorous cocktail party. Only as the Higgs field tumbles down to its true vacuum state does inflation come to a halt, and the ordinary course of the Big Bang resume.

The mechanism of inflation, cosmologists cheerfully admit, is rather like one of those Rube Goldberg contraptions in which a door is made to open by means of a sequence that includes a flashing neon light, an insulting message in a bottle, a prizefighter wearing patent-leather shoes, and a boa constrictor with an aversion to milk. Nonetheless, they add, inflation provides a natural and plausible explanation for the fact that the CBR is uniform in temperature. If the universe under standard Big Bang cosmology is too large to allow a coordinating physical signal to reach every part of the CBR, then one redemptive idea is to cast around for a universe smaller than the standard one. This, inflation provides. Within an inflationary universe, the CBR owes its uniform temperature to the fact that it has been thoroughly mixed. At the end of the era of recombination, the CBR then surges through space like pre-warmed soup.

Inflation is an idea that has gripped the community of cosmologists. Whether it has advanced their scientific agenda is another question. As we have seen, standard Big Bang cosmology requires that features of the early universe such as the temperature of the CBR be set arbitrarily. This has seemed intellectually repugnant to many physicists: the goal of science is to reduce the arbitrariness of description. But inflationary cosmology has arbitrary features of its own, which, displaced from one corner of the theory, have a habit of popping up in another. "The need for fine-tuning of the universe," the physicist David Lindley observed of Guth's proposal, "has been obviated by fine-tuning the Higgs mechanism instead." So it has.

Soon after its introduction, Guth's model of inflation required adjustment. The Higgs field has been replaced by scalar fields, which, as Guth admits, "in many cases serve no function other than the driving of inflation." These fields must be carefully chosen if they are to do their work, a fact that Guth again honestly acknowledges: "Their nature cannot be deduced from known physics, and their detailed properties have to be hypothesized."

In an interesting example of inflationary theory self-applied, inflationary fields have undergone an exponential increase of their own. Beyond mere inflation, the sort of thing that with great heartiness simply blows the universe up, there is chaotic inflation and even "eternal inflation," both of them the creations of the cosmologist Andrei Linde. Almost all cosmologists have a favored scheme; when not advancing their own, they occupy themselves enumerating the deficiencies of the others.

### *Red Stars at Night*

**S**TREAMING IN from space, light reaches the earth like a river rich in information, the stars in the sky having inscribed strange and secret messages on its undulations. The universe is very large, light has always whispered; the nearest galaxy to our own -- Andromeda--is more than two million light years away. But the universe has also seemed relatively static, and this, too, light suggests, the stars appearing where they have always appeared, the familiar dogs and bears and girdled archers of the constellations making their appointed rounds in the sky each night.

More than anything else, it is this impression that Big Bang cosmology rejects. The cool gray universe, current dogma holds, is a place of extraordinary violence, the galaxies receding from one another, the skin of creation stretching at every spot in space, the whole colossal structure blasting apart with terrible force. And this message is inscribed in light as well.

In one of its incarnations, light represents an undulation of the electromagnetic field; its source is the excitable atom itself, with electrons bouncing from one orbit to another and releasing energy as a result. Each atom has a spectral signature, a distinctive electromagnetic frequency. The light that streams in from space thus reveals something about the composition of the galaxies from which it was sent.

In the 1920's, the characteristic signature of hydrogen was detected in various far-flung galaxies. And then an odd discovery was made. Examining a very small sample of twenty or so galaxies, the American astronomer V. M. Slipher observed that the frequency of the hydrogen they sent into space was shifted to the red portion of the spectrum. It was an extraordinary observation, achieved by means of primitive equipment. Using a far more sophisticated telescope, Edwin Hubble made the same discovery in the late 1920's after Slipher had (foolishly) turned his attention elsewhere.

The galactic redshift, Hubble realized, was an exceptionally vivid cosmic clue, a bit of evidence from far away and long ago, and like all clues its value lay in the questions it prompted. Why should galactic light be shifted to the red and not the blue portions of the spectrum? Why, for that matter, should it be shifted at all?

An invigorating stab in the dark now followed. The pitch of a siren is altered as a police car disappears down the street, the sound waves carrying the noise stretched by the speed of the car itself. This is the familiar Doppler effect. Something similar, Hubble

conjectured, might explain the redshift of the galaxies, with the distortions in their spectral signature arising as a reflection of their recessional velocity as they disappeared into the depths.

Observations and inferences resolved themselves into a quantitative relationship. The redshift of a galaxy, cosmologists affirm, and so its recessional velocity, is proportional to its distance and inversely proportional to its apparent brightness or flux. The relationship is known as Hubble's law, even though Hubble himself regarded the facts at his disposal with skepticism.

Hubble's law anchors Big Bang cosmology to the real world. Many astronomers have persuaded themselves that the law represents an observation, almost as if, peering through his telescope, Hubble had noticed the galaxies zooming off into the far distance. This is nonsense. Hubble's law consolidates a number of very plausible intellectual steps. The light streaming in from space is relieved of its secrets by means of ordinary and familiar facts, but even after the facts are admitted into evidence, the relationship among the redshift of the galaxies, their recessional velocity, and their distance represents a complicated inference, an intellectual leap.

**T**HE BIG BANG rests on the hypothesis that the universe is expanding, and in the end the plausibility of its claims will depend on whether the universe *is* expanding. Astronomers can indeed point to places in the sky where the redshift of the galaxies appears to be a linear function of their distance. But in astrophysics, as in evolutionary biology, it is failure rather than success that is of significance. The astrophysical literature contains interesting and disturbing evidence that the linear relationship at the heart of Hubble's law by no means describes the facts fully.

At the end of World War II, astronomers discovered places in the sky where charged particles moving in a magnetic field sent out strong signals in the radio portion of the spectrum. Twenty years later, Alan Sandage and Thomas Mathews identified the source of such signals with optically discernible points in space. These are the quasars--*quasi stellar radio sources*.

Quasars have played a singular role in astrophysics. In the mid-1960's, Maarten Schmidt discovered that their spectral lines were shifted massively to the red. If Hubble's law were correct, quasars should be impossibly far away, hurtling themselves into oblivion at the far edge of space and time. But for more than a decade, the American astronomer Halton Arp has drawn the attention of the astronomical community to places in the sky where the expected relationship between redshift and distance simply fails. Embarrassingly enough, many quasars seem bound to nearby galaxies. The results are in plain sight: there on the photographic plate is the smudged record of a galaxy, and there next to it is a quasar, the points of light lined up and looking for all the world as if they were equally luminous.

These observations do not comport with standard Big Bang cosmology. If quasars have very large redshifts, they must (according to Hubble's law) be very far away; if they *seem*

nearby, then either they must be fantastically luminous or their redshift has not been derived from their velocity. The tight tidy series of inferences that has gone into Big Bang cosmology, like leverage in commodity trading, works beautifully in reverse, physicists like speculators finding their expectations canceled by the very processes they had hoped to exploit.

Acknowledging the difficulty, some theoreticians have proposed that quasars have been caught in the process of evolution. Others have scrupled at Arp's statistics. Still others have claimed that his samples are too small, although they have claimed this for every sample presented and will no doubt continue to claim this when the samples number in the billions. But whatever the excuses, a great many cosmologists recognize that quasars mark a point where the otherwise silky surface of cosmological evidence encounters a snag.

WITHIN ANY scientific discipline, bad news must come in battalions before it is taken seriously. Cosmologists can point to any number of cases in which disconcerting evidence has resolved itself in their favor; a decision to regard the quasars with a watchful indifference is not necessarily irrational. The galaxies are another matter. They are central to Hubble's law; it is within the context of galactic observation that the crucial observational evidence for the Big Bang must be found or forged.

The battalions now begin to fill. The American mathematician I.E. Segal and his associates have studied the evidence for galactic recessional velocity over the course of twenty years, with results that are sharply at odds with predictions of Big Bang cosmology. Segal is a distinguished, indeed a great mathematician, one of the creators of modern function theory and a member of the National Academy of Sciences. He has incurred the indignation of the astrophysical community by suggesting broadly that their standards of statistical rigor would shame a sociologist. Big Bang cosmology, he writes,

owes its acceptance as a physical principle primarily to the uncritical and premature representation of [the redshift-distance relationship] as an empirical fact. . . . Observed discrepancies . . . have been resolved by a pyramid of exculpatory assumptions, which are inherently incapable of noncircular substantiation.

These are strong words of remonstration, but they are not implausible. Having constructed an elaborate scientific orthodoxy, cosmologists have acquired a vested interest in its defense. The astrophysicists J.G. Hoessell, J.E. Gunn, and T.X. Thuan, for example, report with satisfaction that within the structures described by G.O. Abell's *Catalog of Bright Cluster Galaxies* (1958), prediction and observation cohere perfectly to support Hubble's law. Abell's catalog is a standard astronomical resource, used by cosmologists everywhere--but it is useless as evidence for Hubble's law. "In determining whether a cluster meets selection criterion," Abell affirms, "it was assumed that their redshifts were proportional to their distance." If this is what Abell *assumed*, there is little point in asking what conclusions he *derived*.

The fact that the evidence in favor of Hubble's law may be biased does not mean that it is untrue; bias may suggest nothing more than a methodological flaw. But Segal is persuaded that when the evidence is soberly considered, it *does* contravene accepted doctrine, statistical sloppiness functioning, as it so often does, simply to conceal the facts.

A statistical inference is compelling only if the samples upon which it rests are objectively compelling. Objectivity, in turn, requires that the process of sampling be both reasonably complete and unbiased. Segal and his colleagues have taken pains to study samples that within the limits of observation are both. Their most recent study contains a detailed parallel analysis of Hubble's law across four wave bands, one that essentially surveys all stellar objects within each band. The analysis is based on new data drawn from the G. de Vaucouleurs survey of bright cluster galaxies, which includes more than 10,000 galaxies. Hubble's own analysis, it is worthwhile to recall, was limited to twenty galaxies.

The results of their analysis are disturbing. The linear relationship that Hubble saw, Segal and his collaborators cannot see and have not found. Rather, the relationship between redshift and flux or apparent brightness that they have studied in a large number of complete samples satisfies a quadratic law, the redshift varying as the square of apparent brightness. "By normal standards of scientific due process," Segal writes, "the results of [Big Bang] cosmology are illusory."

Cosmologists have dismissed Segal's claims with a great snort of indignation. But the discrepancy from Big Bang cosmology that they reveal is hardly trivial. Like evolutionary biologists, cosmologists are often persuaded that they are in command of a structure intellectually powerful enough to accommodate gross discrepancies in the data. This is a dangerous and deluded attitude. Hubble's law embodies a general hypothesis of Big Bang cosmology--namely, that the universe is expanding--and while the law cannot be established by observation, observation *can* establish that it may be false. A statistically responsible body of contravening evidence has revealed something more than an incidental defect. Indifference to its implications amounts to a decision to place Big Bang cosmology beyond rational inquiry.

### *Monlam Chemno*

**S**HATEVER THE facts may be, the Big Bang is also an event informed by the majesty of a great physical theory. Einstein published the equations for general relativity in 1915, and more than 80 years later, general relativity remains the only theoretical instrument remotely adequate to the representation of the universe as a whole.

General relativity is first and fundamentally an account of gravity, the force that pulls ballerinas to the ground and that fixes the planets in elliptical orbits around the sun. At the beginning of the scientific era, Isaac Newton described a universe in which space and time are absolute. The measured beating of a great clock is heard, and it is heard everywhere at once. Particles move within the unchanging vault of space. Material

objects attract one another with a force proportional to their mass and inversely proportional to the square of the distance between them.

A metaphysical reorganization is required before Newton's caterpillar can emerge as Einstein's butterfly. The elements of general relativity are physical *processes*, a word signifying something that starts at one time and at one place and that ends at another time and another place, and so crawls along a continuum whose intrinsic structure has four dimensions. Within the arena of these physical processes, the solid structures of the Newtonian universe undergo a dissolution. The great vault of space and the uniformly beating heart dwindle and then disappear: *this* universe is one in which space and time have fused themselves into a single entity, and *its* heart is an ever-changing but reciprocating relationship between space-time and matter. Material objects direct the space and time that surround them to curve, much as a bowling ball deforms the mattress on which it rests; the curvature of space-time determines the path undertaken by physical processes, much as an ant crawling on that mattress must travel a curved path to get where it is going.

Newtonian gravity acts at a distance and as a force, the very bowels of the earth reaching to enfold an object and pull it down. But while Newton was able quantitatively to describe how gravity acts, he was unable to say why it acts at all, the aching attraction of matter for matter having no other explanation than the fact that it is so. General relativity provides an explanation of gravity in terms of the curvature of space and time. No forces are involved, and none is invoked, but gravity nonetheless emerges in this universe as a natural expression of the way the cosmos is constructed.

Freely moving objects, Einstein assumed, follow a path covering the shortest distance between points in space and time. Within the ambit of a large material object, the shortest distance between such points is curved. Ballerinas accelerate toward the center of the earth after being thrown upward by their partners because acceleration is required by the geometry in which they are embedded. In this fashion, gravity disappears as a force but remains as a fact.

If the analysis of gravity is at the center of general relativity, the intellectual tools responsible for its analysis--the equations that describe the ever-changing relationship between curvature and material objects--are responsible as well for its local character. For many years, the most precise and most interesting tests of the theory were conducted within the narrow confines of our own solar system. Cosmology, however, is a *global* study, one in which the universe itself is the object of contemplation, and not any of its parts. The conveyance from the local structure of the universe (the sun, the solar system) to the universe as a whole must be negotiated by a daring series of inferences.

In describing matter on a cosmic scale, cosmologists strip the stars and planets, the great galaxies and the bright bursting supernovae, of their uniqueness as places and things and replace them with an imaginary distribution: the matter of the universe is depicted as a great but uniform and homogeneous cloud covering the cosmos equitably in all its secret places. Cosmologists make this assumption because they must. There is no way to deal

with the universe object by object; the equations would be inscrutable, impossible to solve. But however useful the assumption of homogeneity may be mathematically, it is false in the straightforward sense that the distribution of matter in the universe is not homogeneous at all.

Having simplified the contents of the universe, the cosmologist must take care as well, and for the same reason, to strip from the matter that remains any suggestion of particularity or preference in place. The universe, he must assume, is isotropic. It has no center whatsoever, no place toward which things tend, and no special direction or axis of coordination. The thing looks much the same wherever it is observed.

The twin assumptions that the universe is homogeneous and isotropic are not ancillary but indispensable to the hypothesis of an expanding universe; without them, no conclusion can mathematically be forthcoming. Together, these two assumptions are like the figured bass needed to chant what in Tibetan is known as *Monlam Chemno*, the great prayer to the cosmos.

### *Specification in the Dark*

AN EQUATION draws the noose of an identity between two or more items. The field equations of general relativity draw that noose between curvature (the metric structure of the universe) and matter (its stress-energy tensor). But it is one thing to specify an equation, and quite another to solve it.

The mathematician in him having taken command, Einstein endeavored in 1917 to provide cosmological solutions for the field equations of his own theory. He struggled with increasing vexation. The models he was able to derive indicated that the radius of the universe was either expanding or contracting; it was a conclusion that offended his aesthetic sensibilities. By adding a parameter to his equations--the so-called cosmological constant--he was in the end able to discover a static solution, one that revealed a universe finite in extent, but unbounded, like the surface of a sphere. This static solution has a habit of dropping from the view of cosmologists, who routinely aver that Einstein's theory of general relativity uniquely specifies an expanding universe. Not so.

Einstein had hoped that the equations of general relativity would determine a single world model, or cosmic blueprint. In this he was destined to be disappointed. Months after he discovered one solution of the field equations, Willem de Sitter discovered another. In de Sitter's universe, there is no matter whatsoever, the place looking rather like a dance hall in which the music can be heard but no dancers seen, radiation filling the empty spaces and ricocheting from one end of creation to another.

In the 1920's, both Aleksandr Friedmann and Georges Lemaître discovered the solutions to the field equations that have dominated cosmology ever since, their work coming to amalgamate itself into a single denomination as Friedmann-Lemaître (FL) cosmology. Gone from their models is the cosmological constant (although it is resurrected in various

inflation scenarios), and as a result the universe breathes voluptuously, its radius expanding or contracting with time.

FL cosmology does not assign to the universe a unique geometrical identity, or specify its fate forever; general relativity is mathematically compatible with a number of different physical scenarios. Like the surface of a sphere, the universe may well be closed, the whole thing falling back on itself at the end of time. A certain symmetry prevails, the life of things and all the drama of creation caught between two singularities as the universe traces a trajectory in which its initial effervescent explosion is followed by a subsequent enervating contraction.

Or yet again, the universe may well be open, space and time forever gushing into the void but with ever-decreasing intensity, like an athlete panting in shallow breaths. Such a universe is purely a mathematician's world, one seen only by the exercise of certain obscure mental muscles, and regarded by physicists (and everyone else) with glum distaste.

Or, finally, the universe may be one that occupies the Euclidean space of high-school textbooks and intuition alike, balanced precariously but balanced forever on a knife's edge between expansion and contraction.

If its predictive capacities seem unstable, FL cosmology has other peculiarities as well. Whatever the specific form its solutions take, they are alike in assigning dynamic properties to the universe as a whole. The classical distinction between the eternal vault of space and time and its entirely perishable contents has disappeared. The universe in FL cosmology is *itself* bound to the wheel of being, with space and time no more permanent than water and air. Light blazes, the show commences, and like some magnificent but mysterious organism, the universe expands with an exuberant rush of energy and floods nothingness with the seeds of being. In this fundamental respect, FL cosmology breaks both with tradition and with common sense.

### *At Time Zero*

THE INTERPRETATION of a physical theory partakes of a dark art, one in which mathematical concepts are ceded dominion over the physical world. In practicing this art, the mathematician, like the necromancer that he is, is always liable to the temptation of confusing the structures over which he presides with things in the real world.

On the assumption--on the *assumption*--that the universe is expanding, it is irresistibly tempting to run time backward until the far-flung debris of the cosmos collects itself back into a smaller and smaller area. It seems evident, though, that this process of contraction and collapse may be continued only so far. An apple may be divided in halves, and then thirds, and then quarters, but even though the mathematical sequence of one half, one third, one fourth, and so on contains infinitely many terms, and converges ultimately to zero, the apple itself may be divided only finitely many times.

This straightforward point has been the source of grave confusion. "The universe," the astronomer Joseph Silk writes, "began at time zero in a state of infinite density." It is there that (by definition) a *singularity* may be found. "Of course," Silk adds, "the phrase 'a state of infinite density' is completely unacceptable as a physical description of the universe. . . . An infinitely dense universe [is] where the laws of physics, and even space and time, break down."

These are not words that inspire confidence. Does the phrase "a state of infinite density" describe a physical state of affairs or not? If it does, the description is uninformative by virtue of being "completely unacceptable." If it does not, the description is uninformative by virtue of being completely irrelevant. But if the description is either unacceptable or irrelevant, what reason is there to believe that the universe began in an initial singularity? Absent an initial singularity, what reason is there to believe that the universe began at all?

When prominent cosmologists tie them-selves in knots, charity tends to assign the blame to the medium in which they are navigating--books for a general audience--rather than the message they are conveying. But when it comes to the singularities, the knots form in *every* medium, evidence that the message is at fault and not the other way around.

Cosmologists often claim that the mathematicians among them have demonstrated what they themselves may be unable clearly to express. In a passage that is typical, the astrophysicist Kip Thorne writes that "[Stephen] Hawking and [Roger] Penrose in 1970 proved--without any idealizing assumptions--that our universe must have had a space-time singularity at the beginning of its Big Bang expansion." But while it is true that Hawking and Penrose proved something, what they demonstrated remains within the gerbil wheel of mathematics; any additional inference requires a connection that the mathematician is not in a position to provide.

The concept of a singularity belongs *essentially* to mathematics. Singularities are not experimentally accessible objects. They cannot be weighed, measured, assessed, replicated, balanced, or seen by any modality of the senses. Within certain mathematical contexts, the concept has real content. An ordinary curve goes up one side of the blackboard and down the other; it *changes* its direction at a singular point. There are singularities within the calculus, and singularities in complex function theory where imaginary numbers loiter, and singularities in the space of smooth maps. There are singularities within general relativity as well, but the term covers a variety of cases, and the singularities within general relativity are distinctly odd.

In most mathematical theories a natural distinction is drawn between a figure and its background: a curve arcs within the broader ambit of an enveloping space, a mapping is easily distinguished from the spaces it connects. Typically, it is the figure that admits of a singularity: the curve changes its direction or the mapping breaks down, while the background stays the same. But in general relativity, it is the *background* that suffers a singularity, the very fabric of space and time giving way with a rip as curvature zooms off to infinity and space and time contort themselves. For the purposes of describing such singularities, the usual mathematical techniques are unavailing.

That having been said, here is what Hawking and Penrose brought under the control of a mathematical demonstration. The setting is FL cosmology and *only* FL cosmology. There are three kinds of universe to consider, and innumerable many species within each type. Those that are open and forever gushing into the void are called hyperbolic. Within almost all of those hyperbolic universes, almost all processes begin at a point in the past. Within the two types of universe that remain, there is bound to be at least one process that has begun somewhere in the past.

Despite the tics--"almost all," "at least one"--the Penrose-Hawking theorems do indeed demonstrate that some universes begin in an initial singularity. But the light thrown by the Penrose-Hawking theorems flickers over a mathematical theory and so a mathematical universe. The universe that we inhabit is a physical system. Nothing but grief can come of confusing the one for the other. FL cosmology requires the existence of space-time singularities, but there is nothing in the Penrose-Hawking theorems to suggest that a space-time singularity corresponds to an explosion, or marks the beginning of an expansion, or describes an accessible portion of space and time, or connects itself to any physical state of affairs whatsoever.

Mathematical concepts achieve physical significance only when the theories in which they are embedded are confirmed by experience. If a space-time singularity is not a physical event, no such confirmation can logically be forthcoming. With the argument rolled backward, it follows that if these mathematical theories are not confirmed by experience, then neither have they achieved any physical significance.

It is Einstein who expressed the most reasonable and deeply thought views on this matter. "One may not therefore assume the validity of the [field] equation for very high density of the field and of matter," he remarked, "and one may not conclude that the beginning of the expansion must mean a singularity in the mathematical sense. All we have to realize is that the equations may not be continued over such regions."

The sharp, clean, bracing light that the Big Bang was to have thrown on the very origins of space and time lapses when it is most needed. The relevant equations of general relativity fall silent at precisely the moment we most wish they would speak.

### *The Closing Circle*

LIKE SO many haunting human stories, the scientific story of the Big Bang is circular in the progression of its ideas and circular thus in its deepest nature. Cosmologists have routinely assumed that the universe is expanding because they have been persuaded of FL cosmology; and they have been persuaded of FL cosmology because they have routinely assumed that the universe is expanding. The pattern would be intellectually convenient if it were intellectually compelling.

If the evidence in favor of Big Bang cosmology is more suspect than generally imagined, its defects are far stronger than generally credited. Whatever else it may be, the universe

is a bright, noisy, energetic place. There are monstrously large galaxies in the skies and countless many suns burning with fierce thermonuclear fires. Black holes are said to loiter here and there, sucking in matter and light and releasing it slowly in the form of radiation. Whence the energy for the show, the place where accounts are settled? The principles of 19th-century physics require that, in one way or another, accounts *must* be settled. Energy is neither created nor destroyed.

Hot Big Bang cosmology appears to be in violation of the first law of thermodynamics. The global energy needed to run the universe has come from nowhere, and to nowhere it apparently goes as the universe loses energy by cooling itself.

This contravention of thermodynamics expresses, in physical form, a general philosophical anxiety. Having brought space and time into existence, along with everything else, the Big Bang itself remains outside any causal scheme. The creation of the universe remains unexplained by any force, field, power, potency, influence, or instrumentality known to physics--or to man. The whole vast imposing structure organizes itself from absolutely nothing.

This is not simply difficult to grasp. It is incomprehensible.

Physicists, no less than anyone else, are uneasy with the idea that the universe simply popped into existence, with space and time "suddenly switching themselves on." The image of a light switch comes from Paul Davies, who uses it to express a miracle without quite recognizing that it embodies a contradiction. A universe that has *suddenly* switched itself on has accomplished something within time; and yet the Big Bang is supposed to have brought space and time into existence.

Having entered a dark logical defile, physicists often find it difficult to withdraw. Thus, Alan Guth writes in pleased astonishment that the universe really did arise from "essentially . . . nothing at all": as it happens, a false vacuum patch "10<sup>-26</sup> centimeters in diameter" and "10<sup>-32</sup> solar masses." It would appear, then, that "essentially nothing" has both spatial extension and mass. While these facts may strike Guth as inconspicuous, others may suspect that nothingness, like death, is not a matter that admits of degrees.

The attempt to discover some primordial stuff that can be described both as nothing and as something recalls the Maori contemplating the manifold mysteries of *po*. This apparently gives Stephen Hawking pause. "To ask what happened before the universe began," he has written, "is like asking for a point on the Earth at 91 degrees north latitude." We are on the inside of the great sphere of space and time, and while we can see to the boundaries, there is nothing beyond to see if only because there is nothing beyond. "Instead of talking about the universe being created, and maybe coming to an end," Hawking writes, "one should just say: the universe is."

Now this is a conclusion to which mystics have always given their assent; but having concluded that the universe just "is," cosmologists, one might think, would wish to know *why* it is. The question that Hawking wishes to evade disappears as a question in physics

only to reappear as a question in philosophy; we find ourselves traveling in all the old familiar circles.

### *Contract*

STANDING AT the gate of modern time, Isaac Newton forged the curious social pact by which rational men and women have lived ever since. The description of the physical world would be vouchsafed to a particular institution, that of mathematical physics; and it was to the physicists and not the priests, soothsayers, poets, politicians, novelists, generals, mystics, artists, astrologers, warlocks, wizards, or enchanters that society would look for judgments about the nature of the physical world. If knowledge is power, the physicists have, by this arrangement, been given an enormous privilege. But a social arrangement is among other things a contract: something is given, but something is expected as well. In exchange for their privilege, the physicists were to provide an account of the physical world at once penetrating, general, persuasive, and true.

Until recently, the great physicists have been scrupulous about honoring the terms of their contract. They have attempted with dignity to respect the distinction between what is known and what is not. Even quantum electrodynamics, the most successful theory ever devised, was described honestly by its founder, Richard Feynman, as resting on a number of unwholesome mathematical tricks.

This scrupulousness has lately been compromised. The result has been the calculated or careless erasure of the line separating disciplined physical inquiry from speculative metaphysics. Contemporary cosmologists feel free to say anything that pops into their heads. Unhappy examples are everywhere: absurd schemes to model time on the basis of the complex numbers, as in Stephen Hawking's *A Brief History of Time*; bizarre and ugly contraptions for cosmic inflation; universes multiplying beyond the reach of observation; white holes, black holes, worm holes, and naked singularities; theories of every stripe and variety, all of them uncorrected by any criticism beyond the trivial.

The physicists carry on endlessly because they can. Just recently, for example, [Lee Smolin](#), a cosmologist at the University of Pennsylvania, has offered a Darwinian interpretation of cosmology, a theory of "cosmological natural selection." On Smolin's view, the Big Bang happened within a black hole; new universes are bubbling up all the time, each emerging from its own black hole and each provided with its own set of physical laws, so that the very concept of a law of nature is shown to be a part of the mutability of things.

There is, needless to say, no evidence whatsoever in favor of this preposterous theory. The universes that are bubbling up are unobservable. So, too, are the universes that have bubbled up and those that will bubble up in the future. Smolin's theories cannot be confirmed by experience. Or by anything else. What law of nature could reveal that the laws of nature are contingent? Yet the fact that when Smolin's theory is self-applied it

self-destructs has not prevented physicists like Alan Guth, Roger Penrose, and Martin Rees from circumspectly applauding the effort nonetheless.

A scientific crisis has historically been the excuse to which scientists have appealed for the exculpation of damaged doctrines. Smolin is no exception. "We are living," he writes, "through a period of scientific crisis." Ordinary men and women may well scruple at the idea that cosmology is in crisis because cosmologists, deep down, have run out of interesting things to say, but in his general suspicions Smolin is no doubt correct. What we are discovering is that many areas of the universe are apparently protected from our scrutiny, like sensitive files sealed from view by powerful encryption codes. However painful, the discovery should hardly be unexpected. Beyond every act of understanding, there is an abyss.

Like Darwin's theory of evolution, Big Bang cosmology has undergone that curious social process in which a scientific theory is promoted to a secular myth. The two theories serve as points of certainty in an intellectual culture that is otherwise disposed to give the benefit of the doubt to doubt itself. It is within the mirror of these myths that we have come to see ourselves. But if the promotion of theory into myth satisfies one human agenda, it violates another. Myths are quite typically false, and science is concerned with truth. Human beings, it would seem, may make scientific theories or they may make myths, but with respect to the same aspects of experience, they cannot quite do both.

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# On the Origins of Life

*David Berlinski*

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*For those who are studying aspects of the origin of life, the question no longer seems to be whether life could have originated by chemical processes involving non-biological components but, rather, what pathway might have been followed.*

—National Academy of Sciences (1996)

IT IS 1828, a year that encompassed the death of Shaka, the Zulu king, the passage in the United States of the Tariff of Abominations, and the battle of Las Piedras in South America. It is, as well, the year in which the German chemist Friedrich Wöhler announced the synthesis of urea from cyanic acid and ammonia.

Discovered by H.M. Roulle in 1773, urea is the chief constituent of urine. Until 1828, chemists had assumed that urea could be produced only by a living organism. Wöhler provided the most convincing refutation imaginable of this thesis. His synthesis of urea was noteworthy, he observed with

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some understatement, because “it furnishes an example of the artificial production of an organic, indeed a so-called animal substance, from inorganic materials.”\*

Wöhler’s work initiated a revolution in chemistry; but it also initiated a revolution in thought. To the extent that living systems are chemical in their nature, it became possible to imagine that they might be chemical in their origin; and if chemical in their origin, then plainly physical in their nature, and hence a part of the universe that can be explained in terms of “the model for what science should be.”\*

In a letter written to his friend, Sir Joseph Hooker, several decades after Wöhler’s announcement, Charles Darwin allowed himself to speculate. Invoking “a warm little pond” bubbling up in the dim inaccessible past, Darwin imagined that given “ammonia and phosphoric salts, light, heat, electricity, etc. present,” the spontaneous genera-

\* I used this phrase, borrowed from the mathematicians J.H. Hubbard and B.H. West, in “On the Origins of the Mind” (COMMENTARY, November 2004). The idea that science must conform to a certain model of inquiry is familiar. Hubbard and West identify that model with differential equations, the canonical instruments throughout physics and chemistry.

But the essentials of the model, it seems to me, lie less with the particular means in which it is expressed and more with the constraints that it must meet. The idea behind the “model for what science should be” is that whatever may be a system’s initial conditions, or starting point, the laws of its development must be both unique and stable. When they are, the system that results is well posed, and so a proper object of contemplation.

tion of a “protein compound” might follow, with this compound “ready to undergo still more complex changes” and so begin Darwinian evolution itself.

Time must now be allowed to pass. Shall we say 60 years or so? Working independently, J.B.S. Haldane in England and A.I. Oparin in the Soviet Union published influential studies concerning the origin of life. Before the era of biological evolution, they conjectured, there must have been an era of *chemical* evolution taking place in something like a pre-biotic soup. A reducing atmosphere prevailed, dominated by methane and ammonia, in which hydrogen atoms, by donating their electrons (and so “reducing” their number), promoted various chemical reactions. Energy was at hand in the form of electrical discharges, and thereafter complex hydrocarbons appeared on the surface of the sea.

The publication of Stanley Miller’s paper, “A Production of Amino Acids Under Possible Primitive Earth Conditions,” in the May 1953 issue of *Science* completed the inferential arc initiated by Friedrich Wöhler 125 years earlier. Miller, a graduate student, did his work at the instruction of Harold Urey. Because he did not contribute directly to the experiment, Urey insisted that his name not be listed on the paper itself. But their work is now universally known as the Miller-Urey experiment, providing evidence that a good deed can be its own reward.

By drawing inferences about pre-biotic evolution from ordinary chemistry, Haldane and Oparin had opened an imaginary door. Miller and Urey barged right through. Within the confines of two beakers, they re-created a simple pre-biotic environment. One beaker held water; the other, connected to the first by a closed system of glass tubes, held hydrogen cyanide, water, methane, and ammonia. The two beakers were thus assumed to simulate the pre-biotic ocean and its atmosphere. Water in the first could pass by evaporation to the gases in the second, with vapor returning to the original alembic by means of condensation.

Then Miller and Urey allowed an electrical spark to pass continually through the mixture of gases in the second beaker, the gods of chemistry controlling the reactions that followed with very little or no human help. A week after they had begun their experiment, Miller and Urey discovered that in addition to a tarry residue—its most notable product—their potent little planet had yielded a number of the amino acids found in living systems.

The effect among biologists (and the public) was

electrifying—all the more so because of the experiment’s methodological genius. Miller and Urey had done nothing. Nature had done everything. The experiment alone had parted the cloud of unknowing.

### *The Double Helix*

**I**N APRIL 1953, just four weeks before Miller and Urey would report their results in *Science*, James Watson and Francis Crick published a short letter in *Nature* entitled “A Structure for Deoxyribose Nucleic Acid.” The letter is now famous, if only because the exuberant Crick, at least, was persuaded that he and Watson had discovered the secret of life. In this he was mistaken: the secret of life, along with its meaning, remains hidden. But in deducing the structure of deoxyribose nucleic acid (DNA) from X-ray diffraction patterns and various chemical details, Watson and Crick *had* discovered the way in which life at the molecular level replicates itself.

Formed as a double helix, DNA, Watson and Crick argued, consists of two twisted strings facing each other and bound together by struts. Each string comprises a series of four nitrogenous bases: adenine (A), guanine (G), thymine (T), and cytosine (C). The bases are nitrogenous because their chemical activity is determined by the electrons of the nitrogen atom, and they are bases because they are one of two great chemical clans—the other being the acids, with which they combine to form salts.

Within each strand of DNA, the nitrogenous bases are bound to a sugar, deoxyribose. Sugar molecules are in turn linked to each other by a phosphate group. When nucleotides (A, G, T, or C) are connected in a sugar-phosphate chain, they form a polynucleotide. In living DNA, two such chains face each other, their bases touching fingers, A matched to T and C to G. The coincidence between bases is known now as Watson-Crick base pairing.

“It has not escaped our notice,” Watson and Crick observed, “that the specific pairings we have postulated immediately suggests a possible *copying mechanism* for the genetic material” (emphasis added). Replication proceeds, that is, when a molecule of DNA is unzipped along its internal axis, dividing the hydrogen bonds between the bases. Base pairing then works to prompt both strands of a separated double helix to form a double helix anew.

So Watson and Crick conjectured, and so it has proved.

### The Synthesis of Protein

**T**OGETHER WITH Francis Crick and Maurice Wilkins, James Watson received the Nobel Prize for medicine in 1962. In his acceptance speech in Stockholm before the king of Sweden, Watson had occasion to explain his original research goals. The first was to account for genetic replication. This, he and Crick had done. The second was to describe the “way in which genes control protein synthesis.” This, he was in the course of doing.

DNA is a large, long, and stable molecule. As molecules go, it is relatively inert. It is the proteins, rather, that handle the day-to-day affairs of the cell. Acting as enzymes, and so as agents of change, proteins make possible the rapid metabolism characteristic of modern organisms.

Proteins are formed from the alpha-amino acids, of which there are twenty in living systems. The prefix “alpha” designates the position of the crucial carbon atom in the amino acid, indicating that it lies adjacent to (and is bound up with) a carboxyl group comprising carbon, oxygen, again oxygen, and hydrogen. And the proteins are polymers: like DNA, their amino-acid constituents are formed into molecular chains.

But just how does the cell manage to link amino acids to form specific proteins? This was the problem to which Watson alluded as the king of Sweden, lost in a fog of admiration, nodded amiably.

**T**HE SUCCESS of Watson-Crick base pairing had persuaded a number of molecular biologists that DNA undertook protein synthesis by the same process—the formation of symmetrical patterns or “templates”—that governed its replication. After all, molecular replication proceeded by the divinely simple separation-and-recombination of matching (or symmetrical) molecules, with each strand of DNA serving as the template for another. So it seemed altogether plausible that DNA would likewise serve a template function for the amino acids.

It was Francis Crick who in 1957 first observed that this was most unlikely. In a note circulated privately, Crick wrote that “if one considers the physico-chemical nature of the amino-acid side chains, we do not find complementary features on the nucleic acids. Where are the knobby hydrophobic . . . surfaces to distinguish valine from leucine and isoleucine? Where are the charged groups, in specific positions, to go with acidic and basic amino acids?”

Should anyone have missed his point, Crick made it again: “I don’t think that anyone looking at

DNA or RNA [ribonucleic acid] would think of them as templates for amino acids.”

Had these observations been made by anyone but Francis Crick, they might have been regarded as the work of a lunatic; but in looking at any textbook in molecular biology today, it is clear that Crick was simply noticing what was under his nose. Just where *are* those “knobby hydrophobic surfaces”? To imagine that the nucleic acids form a template or pattern for the amino acids is a little like trying to imagine a glove fitting over a centipede. But if the nucleic acids did not form a template for the amino acids, then the information they contained—all of the ancient wisdom of the species, after all—could only be expressed by an indirect form of transmission: a *code* of some sort.

**T**HE IDEA was hardly new. The physicist Erwin Schrödinger had predicted in 1945 that living systems would contain what he called a “code script”; and his short, elegant book, *What Is Life?*, had exerted a compelling influence on every molecular biologist who read it. Ten years later, the ubiquitous Crick invoked the phrase “sequence hypothesis” to characterize the double idea that DNA sequences spell a message *and* that a code is required to express it. What remained obscure was both the spelling of the message and the mechanism by which it was conveyed.

The mechanism emerged first. During the late 1950’s, François Jacob and Jacques Monod advanced the thesis that RNA acts as the first in a chain of intermediates leading from DNA to the amino acids.

Single- rather than double-stranded, RNA is a nucleic acid: a chip from the original DNA block. Instead of thymine (T), it contains the base uracil (U), and the sugar that it employs along its backbone features an atom of oxygen missing from deoxyribose. But RNA, Jacob and Monod argued, was more than a mere molecule: it was a messenger, an instrument of conveyance, “transcribing” in one medium a message first expressed in another. Among the many forms of RNA loitering in the modern cell, the RNA bound for duties of transcription became known, for obvious reasons, as “messenger” RNA.

In transcription, molecular biologists had discovered a second fundamental process, a companion in arms to replication. Almost immediately thereafter, details of the code employed by the messenger appeared. In 1961, Marshall Nirenberg and J. Heinrich Matthaei announced that they had discovered a specific point of contact between RNA and the amino acids. And then, in short

order, the full genetic code emerged. RNA (like DNA) is organized into triplets, so that adjacent sequences of three bases are mapped to a single amino acid. Sixty-four triplets (or codons) govern twenty amino acids. The scheme is universal, or almost so.

The elaboration of the genetic code made possible a remarkably elegant model of the modern cell as a system in which sequences of codons within the nucleic acids act at a distance to determine sequences of amino acids within the proteins: commands issued, responses undertaken. A third fundamental biological process thus acquired molecular incarnation. If replication served to divide and then to duplicate the cell's ancestral message, and transcription to re-express it in messenger RNA, "translation" acted to convey that message from messenger RNA to the amino acids.

FOR ALL the boldness and power of this thesis, the details remained on the level of what bookkeepers call general accounting procedures. No one had established a direct—a *physical*—connection between RNA and the amino acids.

Having noted the problem, Crick also indicated the shape of its solution. "I therefore proposed a theory," he would write retrospectively, "in which there were twenty adaptors (one for each amino acid), together with twenty special enzymes. Each enzyme would join one particular amino acid to its own special adaptor."

In early 1969, at roughly the same time that a somber Lyndon Johnson was departing the White House to return to the Pedernales, the adaptors whose existence Crick had predicted came into view. There were twenty, just as he had suggested. They were short in length; they were specific in their action; and they were nucleic acids. Collectively, they are now designated "transfer" RNA (tRNA).

Folded like a cloverleaf, transfer RNA serves physically as a bridge between messenger RNA and an amino acid. One arm of the cloverleaf is called the anti-coding region. The three nucleotide bases that it contains are curved around the arm's bulblet; they are matched by Watson-Crick base pairing to bases on the messenger RNA. The other end of the cloverleaf is an acceptor region. It is here that an amino acid must go, with the structure of tRNA suggesting a complicated female socket waiting to be charged by an appropriate male amino acid.

The adaptors whose existence Crick had predicted served dramatically to confirm his hypothesis that such adaptors were needed. But although

they brought about a physical connection between the nucleic and the amino acids, the fact that they were themselves nucleic acids raised a question: in the unfolding molecular chain, just what acted to adapt the adaptors to the amino acids? And this, too, was a problem Crick both envisaged and solved: his original suggestion mentioned both adaptors (nucleic acids) and their *enzymes* (proteins).

And so again it proved. The act of matching adaptors to amino acids is carried out by a family of enzymes, and thus by a family of proteins: the aminoacyl-tRNA synthetases. There are as many such enzymes as there are adaptors. The prefix "aminoacyl" indicates a class of chemical reactions, and it is in aminoacylation that the cargo of a carboxyl group is bonded to a molecule of transfer RNA.

Collectively, the enzymes known as synthetases have the power both to recognize specific codons and to select their appropriate amino acid under the universal genetic code. Recognition and selection are ordinarily thought to be cognitive acts. In psychology, they are poorly understood, but within the cell they have been accounted for in chemical terms and so in terms of "the model for what science should be."

With tRNA appropriately charged, the molecule is conveyed to the ribosome, where the task of assembling sequences of amino acids is then undertaken by still another nucleic acid, ribosomal RNA (rRNA). By these means, the modern cell is at last subordinated to a rich narrative drama. To repeat:

*Replication* duplicates the genetic message in DNA.

*Transcription* copies the genetic message from DNA to RNA.

*Translation* conveys the genetic message from RNA to the amino acids—whereupon, in a fourth and final step, the amino acids are assembled into proteins.

### *The Central Dogma*

IT WAS once again Francis Crick, with his remarkable gift for impressing his authority over an entire discipline, who elaborated these facts into what he called the central dogma of molecular biology. The cell, Crick affirmed, is a divided kingdom. Acting as the cell's administrators, the nucleic acids embody all of the requisite wisdom—where to go, what to do, how to manage—in the specific sequence of their nucleotide bases. Administration then proceeds by the transmission of information *from* the nucleic acids *to* the proteins.

The central dogma thus depicts an arrow moving one way, from the nucleic acids to the proteins, and never the other way around. But is anything ever routinely returned, arrow-like, from its target? This is not a question that Crick considered, although in one sense the answer is plainly no. Given the modern genetic code, which maps four nucleotides onto twenty amino acids, there can be no inverse code going in the opposite direction; an inverse mapping is mathematically impossible.

But there is another sense in which Crick's central dogma does engender its own reversal. If the nucleic acids are the cell's administrators, the proteins are its chemical executives: both the staff and the stuff of life. The molecular arrow goes one way with respect to information, but it goes the other way with respect to chemistry.

Replication, transcription, and translation represent the grand unfolding of the central dogma as it proceeds in one direction. The chemical activities initiated by the enzymes represent the grand unfolding of the central dogma as it goes in the other. Within the cell, the two halves of the central dogma combine to reveal a *system of coded chemistry*, an exquisitely intricate but remarkably coherent temporal tableau suggesting a great army in action.

From these considerations a familiar figure now emerges: the figure of a chicken and its egg. Replication, transcription, and translation are all under the control of various enzymes. But enzymes are proteins, and these particular proteins are specified by the cell's nucleic acids. DNA requires the enzymes in order to undertake the work of replication, transcription, and translation; the enzymes require DNA in order to initiate it. The nucleic acids and the proteins are thus profoundly coordinated, each depending upon the other. Without aminoacyl-tRNA synthetase, there is no translation from RNA; but without DNA, there is no synthesis of aminoacyl-tRNA synthetase.

If the nucleic acids and their enzymes simply chased each other forever around the same cell, the result would be a vicious circle. But life has elegantly resolved the circle in the form of a spiral. The aminoacyl-tRNA synthetase that is required to complete molecular translation enters a given cell from its progenitor or "maternal" cell, where it is specified by that cell's DNA. The enzymes required to make the maternal cell's DNA do its work enter that cell from *its* maternal line. And so forth.

On the level of intuition and experience, these facts suggest nothing more mysterious than the longstanding truism that life comes only from life. *Omnia viva ex vivo*, as Latin writers said. It is only when they are embedded in various theories about

the *origins of life* that the facts engender a paradox, or at least a question: in the receding molecular spiral, which came first—the chicken in the form of DNA, or its egg in the form of various proteins? And if neither came first, how could life have begun?

### *The RNA World*

IT IS 1967, the year of the Six-Day war in the Middle East, the discovery of the electroweak forces in particle physics, and the completion of a twenty-year research program devoted to the effects of fluoridation on dental caries in Evanston, Illinois. It is also the year in which Carl Woese, Leslie Orgel, and Francis Crick introduced the hypothesis that "evolution based on RNA replication preceded the appearance of protein synthesis" (emphasis added).

By this time, it had become abundantly clear that the structure of the modern cell was not only more complex than other physical structures but complex in poorly understood ways. And yet no matter how far back biologists traveled into the tunnel of time, certain features of the modern cell were still there, a message sent into the future by the last universal common ancestor. Summarizing his own perplexity in retrospect, Crick would later observe that "an honest man, armed with all the knowledge available to us now, could only state that, in some sense, the origin of life appears at the moment to be almost a miracle." Very wisely, Crick would thereupon determine never to write another paper on the subject—although he did affirm his commitment to the theory of "directed panspermia," according to which life originated in some other portion of the universe and, for reasons that Crick could never specify, was simply sent here.

But that was later. In 1967, the argument presented by Woese, Orgel, and Crick was simple. Given those chickens and their eggs, *something* must have come first. Two possibilities were struck off by a process of elimination. DNA? Too stable and, in some odd sense, too perfect. The proteins? Incapable of dividing themselves, and so, like molecular eunuchs, useful without being fecund. That left RNA. While it was not obviously the right choice for a primordial molecule, it was not obviously the wrong choice, either.

The hypothesis having been advanced—if with no very great sense of intellectual confidence—biologists differed in its interpretation. But they did concur on three general principles. First: that at some time in the distant past, RNA rather than DNA controlled genetic replication. Second: that

Watson-Crick base pairing governed ancestral RNA. And third: that RNA once carried on chemical activities of the sort that are now entrusted to the proteins. The paradox of the chicken and the egg was thus resolved by the hypothesis that the chicken *was* the egg.

The independent discovery in 1981 of the ribozyme—a ribonucleic enzyme—by Thomas Cech and Sidney Altman endowed the RNA hypothesis with the force of a scientific conjecture. Studying the ciliated protozoan *Tetrahymena thermophila*, Cech discovered to his astonishment a form of RNA capable of inducing cleavage. Where an enzyme might have been busy pulling a strand of RNA apart, there was a ribozyme doing the work instead. That busy little molecule served not only to give instructions: apparently it took them as well, and in any case it did what biochemists had since the 1920's assumed could only be done by an enzyme and hence by a protein.

In 1986, the biochemist Walter Gilbert was moved to assert the existence of an entire RNA “world,” an ancestral state promoted by the magic of this designation to what a great many biologists would affirm as fact. Thus, when the molecular biologist Harry Noller discovered that protein synthesis within the contemporary ribosome is catalyzed by ribosomal RNA (rRNA), and not by any of the familiar, old-fashioned enzymes, it appeared “almost certain” to Leslie Orgel that “there once *was* an RNA world” (emphasis added).

### *From Molecular Biology to the Origins of Life*

IT IS perfectly true that every part of the modern cell carries some faint traces of the past. But these molecular traces are only hints. By contrast, to everyone who has studied it, the ribozyme has appeared to be an authentic relic, a solid and palpable souvenir from the pre-biotic past. Its discovery prompted even Francis Crick to the admission that he, too, wished he had been clever enough to look for such relics before they became known.

Thanks to the ribozyme, a great many scientists have become convinced that the “model for what science should be” is achingly close to encompassing the origins of life itself. “My expectation,” remarks David Liu, professor of chemistry and chemical biology at Harvard, “is that we will be able to reduce this to a very simple series of logical events.” Although often overstated, this optimism is by no means irrational. Looking at the modern cell, biologists propose to reconstruct in time the structures that are now plainly there in space.

Research into the origins of life has thus been

subordinated to a rational three-part sequence, beginning in the very distant past. First, the constituents of the cell were formed and assembled. These included the nucleotide bases, the amino acids, and the sugars. There followed next the emergence of the ribozyme, endowed somehow with powers of self-replication. With the stage set, a system of coded chemistry then emerged, making possible what the molecular biologist Paul Schimmel has called “the theater of the proteins.” Thus did matters proceed from the pre-biotic past to the very threshold of the last universal common ancestor, whereupon, with inimitable gusto, life began to diversify itself by means of Darwinian principles.

This account is no longer fantasy. But it is not yet fact. That is one reason why retracing its steps is such an interesting exercise, to which we now turn.

### *Miller Time*

IT IS perhaps four billion years ago. The first of the great eras in the formation of life has commenced. The laws of chemistry are completely in control of things—what else is there? It is Miller Time, the period marking the transition from inorganic to organic chemistry.

According to the impression generally conveyed in both the popular and the scientific literature, the success of the original Miller-Urey experiment was both absolute and unqualified. This, however, is something of an exaggeration. Shortly after Miller and Urey published their results, a number of experienced geochemists expressed reservations. Miller and Urey had assumed that the pre-biotic atmosphere was one in which hydrogen atoms gave up (reduced) their electrons in order to promote chemical activity. Not so, the geochemists contended. The pre-biotic atmosphere was far more nearly neutral than reductive, with little or no methane and a good deal of carbon dioxide.

Nothing in the intervening years has suggested that these sour geochemists were far wrong. Writing in the 1999 issue of *Peptides*, B.M. Rode observed blandly that “modern geochemistry assumes that the secondary atmosphere of the primitive earth (i.e., after diffusion of hydrogen and helium into space) . . . consisted mainly of carbon dioxide, nitrogen, water, sulfur dioxide, and even small amounts of oxygen.” This is not an environment calculated to induce excitement.

Until recently, the chemically unforthcoming nature of the early atmosphere remained an embarrassing secret among evolutionary biologists, like an uncle known privately to dress in women’s underwear; if biologists were disposed in public to

acknowledge the facts, they did so by remarking that every family has one. This has now changed. The issue has come to seem troubling. A recent paper in *Science* has suggested that previous conjectures about the pre-biotic atmosphere were seriously in error. A few researchers have argued that a reducing atmosphere is not, after all, quite so important to pre-biotic synthesis as previously imagined.

In all this, Miller himself has maintained a far more unyielding and honest perspective. "Either you have a reducing atmosphere," he has written bluntly, "or you're not going to have the organic compounds required for life."

**I**F THE composition of the pre-biotic atmosphere remains a matter of controversy, this can hardly be considered surprising: geochemists are attempting to revisit an era that lies four billion years in the past. The synthesis of pre-biotic chemicals is another matter. Questions about them come under the discipline of laboratory experiments.

Among the questions is one concerning the nitrogenous base cytosine (C). Not a trace of the stuff has been found in any meteor. Nothing in comets, either, so far as anyone can tell. It is not buried in the Antarctic. Nor can it be produced by any of the common experiments in pre-biotic chemistry. Beyond the living cell, it has not been found at all.

When, therefore, M.P. Robertson and Stanley Miller announced in *Nature* in 1995 that they had specified a plausible route for the pre-biotic synthesis of cytosine from cyanoacetaldehyde and urea, the feeling of gratification was very considerable. But it has also been short-lived. In a lengthy and influential review published in the 1999 *Proceedings of the National Academy of Science*, the New York University chemist Robert Shapiro observed that the reaction on which Robertson and Miller had pinned their hopes, although active enough, ultimately went nowhere. All too quickly, the cytosine that they had synthesized transformed itself into the RNA base uracil (U) by a chemical reaction known as deamination, which is nothing more mysterious than the process of getting rid of one molecule by sending it somewhere else.

The difficulty, as Shapiro wrote, was that "the formation of cytosine and the subsequent deamination of the product to uracil occur[ed] at about the same rate." Robertson and Miller had themselves reported that after 120 hours, half of their precious cytosine was gone—and it went faster when their reactions took place in saturated urea. In Shapiro's words, "It is clear that the yield of cy-

tosine would fall to 0 percent if the reaction were extended."

If the central chemical reaction favored by Robertson and Miller was self-defeating, it was also contingent on circumstances that were unlikely. Concentrated urea was needed to prompt their reaction; an outhouse whiff would not do. For this same reason, however, the pre-biotic sea, where concentrates disappear too quickly, was hardly the place to begin—as anyone who has safely relieved himself in a swimming pool might confirm with guilty satisfaction. Aware of this, Robertson and Miller posited a different set of circumstances: in place of the pre-biotic soup, drying lagoons. In a fine polemical passage, their critic Shapiro stipulated what would thereby be required:

An isolated lagoon or other body of seawater would have to undergo extreme concentration. . . .

It would further be necessary that the residual liquid be held in an impermeable vessel [in order to prevent cross-reactions].

The concentration process would have to be interrupted for some decades . . . to allow the reaction to occur.

At this point, the reaction would require quenching (perhaps by evaporation to dryness) to prevent loss by deamination.

At the end, one would have a batch of urea in solid form, containing some cytosine (and urea).

Such a scenario, Shapiro remarked, "cannot be excluded as a rare event on early earth, but it cannot be termed plausible."

**L**IKE CYTOSINE, sugar must also make an appearance in Miller Time, and, like cytosine, it too is difficult to synthesize under plausible pre-biotic conditions.

In 1861, the German chemist Alexander Butlerow created a sugar-like substance from a mixture of formaldehyde and lime. Subsequently refined by a long line of organic chemists, Butlerow's so-called formose reaction has been an inspiration to origins-of-life researchers ever since.

The reaction is today initiated by an alkalinizing agent, such as thallium or lead hydroxide. There follows a long induction period, with a number of intermediates bubbling up. The formose reaction is auto-catalytic in the sense that it keeps on going: the carbohydrates that it generates serve to prime the reaction in an exponentially growing feedback loop until the initial stock of formaldehyde is exhausted. With the induction over, the formose reaction yields a number of complex sugars.

Nonetheless, it is not sugars in general that are wanted from Miller Time but a particular form of sugar, namely, ribose—and not simply ribose but dextro ribose. Compounds of carbon are naturally right-handed or left-handed, depending on how they polarize light. The ribose in living systems is right-handed, hence the prefix “dextro.” But the sugars exiting the formose reaction are racemic, that is, both left- and right-handed, and the yield of usable ribose is negligible.

While nothing has as yet changed the fundamental fact that it is very hard to get the right kind of sugar from any sort of experiment, in 1990 the Swiss chemist Albert Eschenmoser was able to change substantially the way in which the sugars appeared. Reaching with the hand of a master into the formose reaction itself, Eschenmoser altered two molecules by adding a phosphate group to them. This slight change prevented the formation of the alien sugars that cluttered the classical formose reaction. The products, Eschenmoser reported, included among other things a mixture of ribose-2,4,-diphosphate. Although the mixture was racemic, it did contain a molecule close to the ribose needed by living systems. With a few chemical adjustments, Eschenmoser could plausibly claim, the pre-biotic route to the synthesis of sugar would lie open.

It remained for skeptics to observe that Eschenmoser’s ribose reactions were critically contingent on Eschenmoser himself, and at two points: the first when he attached phosphate groups to a number of intermediates in the formose reaction, and the second when he removed them.

What had given the original Miller-Urey experiment its power to excite the imagination was the sense that, having set the stage, Miller and Urey exited the theater. By contrast, Eschenmoser remained at center stage, giving directions and in general proving himself indispensable to the whole scene.

Events occurring in Miller Time would thus appear to depend on the large assumption, still unproved, that the early atmosphere was reductive, while two of the era’s chemical triumphs, cytosine and sugar, remain for the moment beyond the powers of contemporary pre-biotic chemistry.

### *From Miller Time to Self-Replicating RNA*

**I**N THE grand progression by which life arose from inorganic matter, Miller Time has been concluded. It is now 3.8 billion years ago. The chemical precursors to life have been formed. A limpid pool of nucleotides is somewhere in existence. A new era is about to commence.

The historical task assigned to this era is a double one: forming chains of nucleic acids from nucleotides, and discovering among them those capable of reproducing themselves. Without the first, there is no RNA; and without the second, there is no life.

In living systems, polymerization or chain-formation proceeds by means of the cell’s invaluable enzymes. But in the grim inhospitable pre-biotic, no enzymes were available. And so chemists have assigned their task to various inorganic catalysts. J.P. Ferris and G. Ertem, for instance, have reported that activated nucleotides bond covalently when embedded on the surface of montmorillonite, a kind of clay. This example, combining technical complexity with general inconclusiveness, may stand for many others.

In any event, polymerization having been concluded—by whatever means—the result was (in the words of Gerald Joyce and Leslie Orgel) “a random ensemble of polynucleotide sequences”: long molecules emerging from short ones, like fronds on the surface of a pond. Among these fronds, nature is said to have discovered a self-replicating molecule. But how?

Darwinian evolution is plainly unavailing in this exercise or that era, since Darwinian evolution *begins* with self-replication, and self-replication is precisely what needs to be explained. But if Darwinian evolution is unavailing, so, too, is chemistry. The fronds comprise “a *random* ensemble of polynucleotide sequences” (emphasis added); but no principle of organic chemistry suggests that aimless encounters among nucleic acids must lead to a chain capable of self-replication.

If chemistry is unavailing and Darwin indisposed, what is left as a mechanism? The evolutionary biologist’s finest friend: sheer dumb luck.

**W**AS NATURE LUCKY? It depends on the payoff and the odds. The payoff is clear: an ancestral form of RNA capable of replication. Without that payoff, there is no life, and obviously, at some point the payoff paid off. The question is the odds.

For the moment, no one knows how precisely to compute those odds, if only because within the laboratory, no one has conducted an experiment leading to a self-replicating ribozyme. But the minimum length or “sequence” that is needed for a contemporary ribozyme to undertake what the distinguished geochemist Gustaf Arrhenius calls “demonstrated ligase activity” is known. It is roughly 100 nucleotides.

Whereupon, just as one might expect, things blow up very quickly. As Arrhenius notes, there are

$4^{100}$  or roughly  $10^{60}$  nucleotide sequences that are 100 nucleotides in length. This is an unfathomably large number. It exceeds the number of atoms contained in the universe, as well as the age of the universe in seconds. If the odds in favor of self-replication are 1 in  $10^{60}$ , no betting man would take them, no matter how attractive the payoff, and neither presumably would nature.

"Solace from the tyranny of nucleotide combinatorials," Arrhenius remarks in discussing this very point, "is sought in the feeling that strict sequence specificity may not be required through all the domains of a functional oligomer, thus making a large number of library items eligible for participation in the construction of the ultimate functional entity." Allow me to translate: why assume that self-replicating sequences are apt to be rare just because they are long? They might have been quite common.

They might well have been. And yet all experience is against it. Why should self-replicating RNA molecules have been common 3.6 billion years ago when they are impossible to discern under laboratory conditions today? No one, for that matter, has ever seen a ribozyme capable of *any* form of catalytic action that is not very specific in its sequence and thus unlike even closely related sequences. No one has ever seen a ribozyme able to undertake chemical action without a suite of enzymes in attendance. No one has ever seen anything like it.

The odds, then, are daunting; and when considered realistically, they are even worse than this already alarming account might suggest. The discovery of a single molecule with the power to initiate replication would hardly be sufficient to establish replication. What template would it replicate *against*? We need, in other words, at least two, causing the odds of their joint discovery to increase from 1 in  $10^{60}$  to 1 in  $10^{120}$ . Those two sequences would have been needed in roughly the same place. And at the same time. And organized in such a way as to favor base pairing. And somehow held in place. And buffered against competing reactions. And productive enough so that their duplicates would not at once vanish in the soundless sea.

In contemplating the discovery by chance of two RNA sequences a mere 40 nucleotides in length, Joyce and Orgel concluded that the requisite "library" would require  $10^{48}$  possible sequences. Given the weight of RNA, they observed gloomily, the relevant sample space would exceed the mass of the earth. And this is the same Leslie Orgel, it will be remembered, who observed that "it was almost certain that there once was an RNA world."

To the accumulating agenda of assumptions,

then, let us add two more: that without enzymes, nucleotides were somehow formed into chains, and that by means we cannot duplicate in the laboratory, a pre-biotic molecule discovered how to reproduce itself.

### From Self-Replicating RNA to Coded Chemistry

A NEW ERA is now in prospect, one that begins with a self-replicating form of RNA and ends with the system of coded chemistry characteristic of the modern cell. The *modern* cell—meaning one that divides its labors by assigning to the nucleic acids the management of information and to the proteins the execution of chemical activity. It is 3.6 billion years ago.

It is with the advent of this era that distinctively conceptual problems emerge. The gods of chemistry may now be seen receding into the distance. The cell's system of coded chemistry is determined by two discrete combinatorial objects: the nucleic acids and the amino acids. These objects are discrete because, just as there are no fractional sentences containing three-and-a-half words, there are no fractional nucleotide sequences containing three-and-a-half nucleotides, or fractional proteins containing three-and-a-half amino acids. They are combinatorial because both the nucleic acids and the amino acids are combined by the cell into larger structures.

But if information management and its administration within the modern cell are determined by a discrete combinatorial system, the *work* of the cell is part of a markedly different enterprise. The periodic table notwithstanding, chemical reactions are not combinatorial, and they are not discrete. The chemical bond, as Linus Pauling demonstrated in the 1930's, is based squarely on quantum mechanics. And to the extent that chemistry is explained in terms of physics, it is encompassed not only by "the model for what science should be" but by the system of differential equations that play so conspicuous a role in every one of the great theories of mathematical physics.

What serves to coordinate the cell's two big shots of information management and chemical activity, and so to coordinate two fundamentally different structures, is the universal genetic code. To capture the remarkable nature of the facts in play here, it is useful to stress the word *code*.

By itself, a code is familiar enough: an arbitrary mapping or a system of linkages between two discrete combinatorial objects. The Morse code, to take a familiar example, coordinates dashes and dots with letters of the alphabet. To note that codes

are arbitrary is to note the distinction between a code and a purely physical connection between two objects. To note that codes embody mappings is to embed the concept of a code in mathematical language. To note that codes reflect a linkage of some sort is to return the concept of a code to its human uses.

In every normal circumstance, the linkage comes first and represents a human achievement, something arising from a point beyond the coding system. (The coordination of dot-dot-dot-dash-dash-dot-dot-dot with the distress signal S-O-S is again a familiar example.) Just as no word explains its own meaning, no code establishes its own nature.

The conceptual question now follows. Can the origins of a system of coded chemistry be explained in a way that makes no appeal whatsoever to the kinds of facts that we otherwise invoke to explain codes and languages, systems of communication, the impress of ordinary words on the world of matter?

In this regard, it is worth recalling that, as Hubert Yockey observes in *Information Theory, Evolution, and the Origin of Life* (2005), “there is no trace in physics or chemistry of the control of chemical reactions by a sequence of any sort or of a code between sequences.”

WRITING IN the 2001 issue of the journal *RNA*, the microbiologist Carl Woese referred ominously to the “dark side of molecular biology.” DNA replication, Woese wrote, is the extraordinarily elegant expression of the structural properties of a single molecule: zip down, divide, zip up. The transcription into RNA follows suit: copy and conserve. In each of these two cases, structure leads to function. But where is the coordinating link between the chemical structure of DNA and the third step, namely, translation? When it comes to translation, the apparatus is baroque: it is incredibly elaborate, and it does not reflect the structure of any molecule.

These reflections prompted Woese to a somber conclusion: if “the nucleic acids cannot in any way recognize the amino acids,” then there is no “fundamental physical principle” at work in translation (emphasis added).

But Woese’s diagnosis of disorder is far too partial; the symptoms he regards as singular are in fact widespread. What holds for translation holds as well for replication and transcription. The nucleic acids cannot directly recognize the amino acids (and vice versa), but they cannot *directly* replicate or transcribe themselves, either. Both replication and

translation are enzymatically driven, and without those enzymes, a molecule of DNA or RNA would do nothing whatsoever. Contrary to what Woese imagines, no fundamental physical principles appear directly at work *anywhere* in the modern cell.

The most difficult and challenging problem associated with the origins of life is now in view. One half of the modern system of coded chemistry—the genetic code and the sequences it conveys—is, from a chemical perspective, arbitrary. The other half of the system of coded chemistry—the activity of the proteins—is, from a chemical perspective, necessary. In life, the two halves are coordinated. The problem follows: how did *that*—the whole system—get here?

THE PREVAILING opinion among molecular biologists is that questions about molecular-biological systems can only be answered by molecular-biological *experiments*. The distinguished molecular biologist Horoaki Suga has recently demonstrated the strengths and the limitations of the experimental method when confronted by difficult conceptual questions like the one I have just posed.

The goal of Suga’s experiment was to show that a set of RNA catalysts (or ribozymes) *could* well have played the role now played in the modern cell by the protein family of aminoacyl synthetases. Until his work, Suga reports, there had been no convincing demonstration that a ribozyme was able to perform the double function of a synthetase—that is, recognizing both a form of transfer RNA and an amino acid. But in Suga’s laboratory, just such a molecule made a now-celebrated appearance. With an amino acid attached to its tail, the ribozyme managed to cleave itself and, like a snake, affix its amino-acid cargo onto its head. What is more, it could conduct this exercise backward, shifting the amino acid from its head to its tail again. The chemical reactions involved acylation: precisely the reactions undertaken by synthetases in the modern cell.

Horoaki Suga’s experiment was both interesting and ingenious, prompting a reaction perhaps best expressed as, “Well, would you look at that!” It has altered the terms of debate by placing a number of new facts on the table. And yet, as so often happens in experimental pre-biotic chemistry, it is by no means clear what interpretation the facts will sustain.

Do Suga’s results really establish the existence of a primitive form of coded chemistry? Although unexpected in context, the coordination he achieved between an amino acid and a form of transfer RNA was never at issue in principle. The question is

whether what was accomplished in establishing a chemical connection between these two molecules was anything like establishing the existence of a *code*. If so, then organic chemistry itself could properly be described as the study of codes, thereby erasing the meaning of a code as an arbitrary mapping between discrete combinatorial objects.

Suga, in summarizing the results of his research, captures rhetorically the inconclusiveness of his achievement. “Our demonstration indicates,” he writes, “that catalytic precursor tRNA’s *could have provided* the foundation of the genetic coding system.” But if the association at issue is not a code, however primitive, it could no more be the “foundation” of a code than a feather could be the foundation of a building. And if it is the foundation of a code, then what has been accomplished has been accomplished by the wrong agent.

In Suga’s experiment, there was no sign that the execution of chemical routines fell under the control of a molecular administration, and no sign, either, that the missing molecular administration had anything to do with executive chemical routines. The missing molecular administrator was, in fact, Suga himself, as his own account reveals. The relevant features of the experiment, he writes, “allow[ed] us to select active RNA molecules with selectivity toward a *desired* amino acid” (emphasis added). Thereafter, it was Suga and his collaborators who “applied *stringent conditions*” to the experiment, undertook “*selective amplification* of the self-modifying RNA molecules,” and “*screened*” vigorously for “self-aminoacetylation activity” (emphasis added throughout).

**I**F NOTHING else, the advent of a system of coded chemistry satisfied the most urgent of imperatives: it was needed and it was found. It was needed because once a system of chemical reactions reaches a certain threshold of complexity, nothing less than a system of coded chemistry can possibly master the ensuing chaos. It was found because, after all, we are here.

Precisely these circumstances have persuaded many molecular biologists that the explanation for the emergence of a system of coded chemistry must in the end lie with Darwin’s theory of evolution. As one critic has observed in commenting on Suga’s experiments, “If a certain result can be achieved by direction in a laboratory by a Suga, surely it can also be achieved by chance in a vast universe.”

A self-replicating ribozyme meets the first condition required for Darwinian evolution to gain purchase. It is by definition capable of replication. And it meets the second condition as well, for, by

means of mistakes in replication, it introduces the possibility of variety into the biological world. On the assumption that subsequent changes to the system follow a law of increasing marginal utility, one can then envisage the eventual emergence of a system of coded chemistry—a system that can be explained in terms of “the model for what science should be.”

It was no doubt out of considerations like these that, in coming up against what he called the “dark side of molecular biology,” Carl Woese was concerned to urge upon the biological community the benefits of “an all-out Darwinian perspective.” But the difficulty with “an all-out Darwinian perspective” is that it entails an all-out Darwinian impediment: notably, the assignment of a degree of foresight to a Darwinian process that the process could not possibly possess.

The hypothesis of an RNA world trades brilliantly on the idea that a divided modern system had its roots in some form of molecular symmetry that was then broken by the contingencies of life. At some point in the transition to the modern system, an ancestral form of RNA must have assigned some of its catalytic properties to an emerging family of proteins. This would have taken place at a given historical moment; it is not an artifact of the imagination. Similarly, at some point in the transition to a modern system, an ancestral form of RNA must have acquired the ability to code for the catalytic powers it was discarding. And this, too, must have taken place at a particular historical moment.

The question, of course, is which of the two steps came first. Without life acquiring some degree of foresight, neither step can be plausibly fixed in place by means of any schedule of selective advantages. How could an ancestral form of RNA have acquired the ability to code for various amino acids before coding was useful? But then again, why should “ribozymes in an RNA world,” as the molecular biologists Paul Schimmel and Shana O. Kelley ask, “have expedited their own obsolescence?”

Could the two steps have taken place simultaneously? If so, there would appear to be very little difference between a Darwinian explanation and the frank admission that a miracle was at work. If no miracles are at work, we are returned to the place from which we started, with the chicken-and-egg pattern that is visible when life is traced backward now appearing when it is traced forward.

It is thus unsurprising that writings embodying Woese’s “all-out Darwinian perspective” are dominated by references to a number of unspecified but mysteriously potent forces and obscure conditional circumstances. I quote without attribution be-

cause the citations are almost generic (emphasis added throughout):

- The aminoacylation of RNA initially *must* have provided some selective advantage.
- The products of this reaction *must* have conferred some selective advantage.
- However, the development of a crude mechanism for controlling the diversity of possible peptides *would* have been advantageous.
- [P]rogressive refinement of that mechanism *would* have provided *further* selective advantage.

And so forth—ending, one imagines, in reduction to the all-purpose imperative of Darwinian theory, which is simply that what was must have been.

### *Now It Is Now*

AT THE conclusion of a long essay, it is customary to summarize what has been learned. In the present case, I suspect it would be more prudent to recall how much has been *assumed*:

First, that the pre-biotic atmosphere was chemically reductive; second, that nature found a way to synthesize cytosine; third, that nature also found a way to synthesize ribose; fourth, that nature found the means to assemble nucleotides into polynucleotides; fifth, that nature discovered a self-replicating molecule; and sixth, that having done all that, nature promoted a self-replicating molecule into a full system of coded chemistry.

These assumptions are not only vexing but progressively so, ending in a serious impediment to thought. That, indeed, may be why a number of biologists have lately reported a weakening of their commitment to the RNA world altogether, and a desire to look elsewhere for an explanation of the emergence of life on earth. “It’s part of a quiet paradigm revolution going on in biology,” the biophysicist Harold Morowitz put it in an interview in *New Scientist*, “in which the radical randomness of Darwinism is being replaced by a much more scientific law-regulated emergence of life.”

Morowitz is not a man inclined to wait for the details to accumulate before reorganizing the vista of modern biology. In a series of articles, he has argued for a global vision based on the biochemistry of living systems rather than on their molecular bi-

ology or on Darwinian adaptations. His vision treats the living system as more fundamental than its particular species, claiming to represent the “universal and deterministic features of *any* system of chemical interactions based on a water-covered but rocky planet such as ours.”

This view of things—metabolism first, as it is often called—is not only intriguing in itself but is enhanced by a firm commitment to chemistry and to “the model for what science should be.” It has been argued with great vigor by Morowitz and others. It represents an alternative to the RNA world. It is a work in progress, and it may well be right. Nonetheless, it suffers from one outstanding defect. There is as yet no evidence that it is true.

IT IS now more than 175 years since Friedrich Wöhler announced the synthesis of urea. It would be the height of folly to doubt that our understanding of life’s origins has been immeasurably improved. But whether it has been immeasurably improved in a way that vigorously confirms the daring idea that living systems are chemical in their origin and so physical in their nature—that is another question entirely.

In “On the Origins of the Mind,” I tried to show that much can be learned by studying the issue from a computational perspective. Analogously, in contemplating the origins of life, much—in fact, more—can be learned by studying the issue from the perspective of coded chemistry. In both cases, however, what seems to lie beyond the reach of “the model for what science should be” is any success beyond the local. All questions about the *global* origins of these strange and baffling systems seem to demand answers that the model itself cannot by its nature provide.

It goes without saying that this is a tentative judgment, perhaps only a hunch. But let us suppose that questions about the origins of the mind and the origins of life do lie beyond the grasp of “the model for what science should be.” In that case, we must either content ourselves with its limitations or revise the model. If a revision also lies beyond our powers, then we may well have to say that the mind and life have appeared in the universe for no very good reason that we can discern.

Worse things have happened. In the end, these are matters that can only be resolved in the way that all such questions are resolved. We must wait and see.

# Commentary

June 1996

## The Deniable Darwin

*David Berlinski*

CHARLES DARWIN presented *On the Origin of Species* to a disbelieving world in 1859—three years after Clerk Maxwell had published “On Faraday’s Lines of Force,” the first of his papers on the electromagnetic field. Maxwell’s theory has by a process of absorption become part of quantum field theory, and so a part of the great canonical structure created by mathematical physics. By contrast, the final triumph of Darwinian theory, although vividly imagined by biologists, remains, along with world peace and Esperanto, on the eschatological horizon of contemporary thought.

“It is just a matter of time,” one biologist wrote recently, reposing his faith in a receding hereafter, “before this fruitful concept comes to be accepted by the public as wholeheartedly as it has accepted the spherical earth and the sun-centered solar system.” Time, however, is what evolutionary biologists have long had, and if general acceptance has not come by now, it is hard to know when it ever will.

IN ITS most familiar, textbook form, Darwin’s theory subordinates itself to a haunting and fantastic

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image, one in which life on earth is represented as a tree. So graphic has this image become that some biologists have persuaded themselves they can *see* the flowering tree standing on a dusty plain, the mammalian twig obliterating itself by anastomosis into a reptilian branch and so backward to the amphibia and then the fish, the sturdy chordate line—our line, *cosa nostra*—moving by slithering stages into the still more primitive trunk of life and so downward to the single irresistible cell that from within its folded chromosomes foretold the living future.

This is nonsense, of course. That densely reticulated tree, with its lavish foliage, is an intellectual construct, one expressing the *hypothesis* of descent with modification. Evolution is a process, one stretching over four billion years. It has not been observed. The past has gone to where the past inevitably goes. The future has not arrived. The present reveals only the detritus of time and chance: the fossil record, and the comparative anatomy, physiology, and biochemistry of different organisms and creatures. Like every other scientific theory, the theory of evolution lies at the end of an inferential trail.

The facts in favor of evolution are often held to be incontrovertible; prominent biologists shake their heads at the obduracy of those who would dispute them. Those facts, however, have been rather less forthcoming than evolutionary biologists might have hoped. If life progressed by an

accumulation of small changes, as they say it has, the fossil record should reflect its flow, the dead stacked up in barely separated strata. But for well over 150 years, the dead have been remarkably diffident about confirming Darwin's theory. Their bones lie suspended in the sands of time—theromorphs and therapsids and things that must have gibbered and then squeaked; but there are gaps in the graveyard, places where there should be intermediate forms but where there is nothing whatsoever instead.<sup>1</sup>

Before the Cambrian era, a brief 600 million years ago, very little is inscribed in the fossil record; but then, signaled by what I imagine as a spectral puff of smoke and a deafening *ta-da!*, an astonishing number of novel biological structures come into creation, and they come into creation at once.

Thereafter, the major transitional sequences are incomplete. Important inferences begin auspiciously, but then trail off, the ancestral connection between *Eusthenopteron* and *Ichthyostega*, for example—the great hinge between the fish and the amphibia—turning on the interpretation of small grooves within *Eusthenopteron*'s intercalary bones. Most species enter the evolutionary order fully formed and then depart unchanged. Where there should be evolution, there is *stasis* instead—the term is used by the paleontologists Stephen Jay Gould and Niles Eldredge in developing their theory of “punctuated equilibria”—with the fire alarms of change going off suddenly during a long night in which nothing happens.

The fundamental core of Darwinian doctrine, the philosopher Daniel Dennett has buoyantly affirmed, “is no longer in dispute among scientists.” Such is the party line, useful on those occasions when biologists must present a single face to their public. But it was to the dead that Darwin pointed for confirmation of his theory; the fact that paleontology does not entirely support his doctrine has been a secret of long standing among paleontologists. “The known fossil record,” Steven Stanley observes, “fails to document a single example of phyletic evolution accomplishing a major morphologic transition and hence offers no evidence that the gradualistic model can be valid.”

Small wonder, then, that when the spotlight of publicity is dimmed, evolutionary biologists evince a feral streak, Stephen Jay Gould, Niles Eldredge, Richard Dawkins, and John Maynard Smith abusing one another roundly like wrestlers grappling in the dark.

### *Pause for the Logician*

**S**WIMMING IN the soundless sea, the shark has survived for millions of years, sleek as a knife blade and twice as dull. *The shark is an organism wonderfully adapted to its environment.* Pause. And then the bright brittle voice of logical folly intrudes: *after all, it has survived for millions of years.*

This exchange should be deeply embarrassing to evolutionary biologists. And yet, time and again, biologists do explain the survival of an organism by reference to its fitness and the fitness of an organism by reference to its survival, the friction between concepts kindling nothing more illuminating than the observation that some creatures have been around for a very long time. “Those individuals that have the most offspring,” writes Ernst Mayr, the distinguished zoologist, “are by definition . . . the fittest ones.” And in *Evolution and the Myth of Creationism*, Tim Berra states that “[f]itness in the Darwinian sense means reproductive fitness—leaving at least enough offspring to spread or sustain the species in nature.”

This is not a parody of evolutionary thinking; it is evolutionary thinking. *Que sera, sera.*

Evolutionary thought is suffused in general with an unwholesome glow. “The belief that an organ so perfect as the eye,” Darwin wrote, “could have been formed by natural selection is enough to stagger anyone.” It is. The problem is obvious. “What good,” Stephen Jay Gould asked dramatically, “is 5 percent of an eye?” He termed this question “excellent.”

The question, retorted the Oxford professor Richard Dawkins, the most prominent representative of ultra-Darwinians, “is not excellent at all”:

Vision that is 5 percent as good as yours or mine is very much worth having in comparison with no vision at all. And 6 percent is better than 5, 7 percent better than 6, and so on up the gradual, continuous series.

But Dawkins, replied Philip Johnson in turn, had carelessly assumed that 5 percent of an eye would see 5 percent as well as an eye, and that is an assumption for which there is little evidence. (A professor of law at the University of California at Berkeley, Johnson has a gift for appealing to the evidence when his opponents invoke theory, and vice versa.)

Having been conducted for more than a century, exchanges of this sort may continue for cen-

<sup>1</sup> A.S. Romer's *Vertebrate Paleontology* (University of Chicago Press, third edition, 1966) may be consulted with profit.

turies more; but the debate is an exercise in irrelevance. What is at work in sight is a visual *system*, one that involves not only the anatomical structures of the eye and forebrain, but the remarkably detailed and poorly understood algorithms required to make these structures work. "When we examine the visual mechanism closely," Karen K. de Valois remarked recently in *Science*, "although we understand much about its component parts, we fail to fathom the ways in which they fit together to produce the whole of our complex visual perception."

These facts suggest a chastening reformulation of Gould's "excellent" question, one adapted to reality: *could a system we do not completely understand be constructed by means of a process we cannot completely specify?*

The intellectually responsible answer to *this* question is that we do not know—we have no way of knowing. But that is not the answer evolutionary theorists accept. According to Daniel Dennett (in *Darwin's Dangerous Idea*), Dawkins is "almost certainly right" to uphold the incremental view, because "Darwinism is basically on the right track." In this, he echoes the philosopher Kim Sterenly, who is also persuaded that "something like Dawkins's stories have *got* to be right" (emphasis added). After all, she asserts, "natural selection is the only possible explanation of complex adaptation."

Dawkins himself has maintained that those who do not believe a complex biological structure may be constructed in small steps are expressing merely their own sense of "personal incredulity." But in countering their animadversions he appeals to his own ability to believe almost anything. Commenting on the (very plausible) claim that spiders could not have acquired their web-spinning behavior by a Darwinian mechanism, Dawkins writes: "It is not impossible at all. That is what I firmly believe and I have some experience of spiders and their webs." It is painful to see this advanced as an argument.

### *Unflagging Success*

DARWIN CONCEIVED of evolution in terms of *small* variations among organisms, variations which by a process of accretion allow one species to change continuously into another. This suggests a view in which living creatures are spread out smoothly over the great manifold of biological possibilities, like colors merging imperceptibly in a color chart.

Life, however, is absolutely nothing like this. Wherever one looks there is singularity, quirki-

ness, oddness, defiant individuality, and just plain weirdness. The male redback spider (*Latrodectus hasselti*), for example, is often consumed during copulation. Such is sexual cannibalism—the result, biologists have long assumed, of "predatory females overcoming the defenses of weaker males." But it now appears that among *Latrodectus hasselti*, the male is complicit in his own consumption. Having achieved intromission, this schnook performs a characteristic somersault, placing his abdomen directly over his partner's mouth. Such is sexual suicide—awfulness taken to a higher power.<sup>2</sup>

It might seem that sexual suicide confers no advantage on the spider, the male passing from ecstasy to extinction in the course of one and the same act. But spiders willing to pay for love are apparently favored by female spiders (no surprise, there); and female spiders with whom they mate, entomologists claim, are less likely to mate again. The male spider perishes; his preposterous line persists.

This explanation resolves one question only at the cost of inviting another: why such bizarre behavior? In no other *Latrodectus* species does the male perform that obliging somersault, offering his partner the oblation of his life as well as his love. Are there general principles that specify sexual suicide among this species, but that forbid sexual suicide elsewhere? If so, what are they?

Once asked, such questions tend to multiply like party guests. If evolutionary theory cannot answer them, what, then, is its use? Why is the Pitcher plant carnivorous, but not the thorn bush, and why does the Pacific salmon require fresh water to spawn, but not the Chilean sea bass? Why has the British thrush learned to hammer snails upon rocks, but not the British blackbird, which often starves to death in the midst of plenty? Why did the firefly discover bioluminescence, but not the wasp or the warrior ant; why do the bees do their dance, but not the spider or the flies; and why are women, but not cats, born without the sleek tails that would make them even more alluring than they already are?

Why? Yes, *why?* The question, simple, clear, intellectually respectable, was put to the Nobel laureate George Wald. "Various organisms try various things," he finally answered, his words functioning as a verbal shrug, "they keep what works and discard the rest."

But suppose the manifold of life were to be given a good solid yank, so that the Chilean sea

<sup>2</sup> The details have been reported in the *New York Times* and in *Science*: evidence that at least some entomologists have a good deal of time on their hands.

bass but not the Pacific salmon required fresh water to spawn, or that ants but not fireflies flickered enticingly at twilight, or that women but not cats were born with lush tails. What then? An inversion of life's fundamental facts would, I suspect, present evolutionary biologists with few difficulties. *Various organisms try various things.* This idea is adapted to any contingency whatsoever, an interesting example of a Darwinian mechanism in the development of Darwinian thought itself.

A comparison with geology is instructive. No geological theory makes it possible to specify precisely a particular mountain's shape; but the underlying process of upthrust and crumbling is well understood, and geologists can specify something like a mountain's *generic* shape. This provides geological theory with a firm connection to reality. A mountain arranging itself in the shape of the letter "A" is not a physically possible object; it is excluded by geological theory.

The theory of evolution, by contrast, is incapable of ruling *anything* out of court. That job must be done by nature. But a theory that can confront any contingency with unflagging success cannot be falsified. Its control of the facts is an illusion.

### *Sheer Dumb Luck*

"**C**HANCE ALONE," the Nobel Prize-winning chemist Jacques Monod once wrote, "is at the source of every innovation, of all creation in the biosphere. Pure chance, absolutely free but blind, is at the very root of the stupendous edifice of creation."

The sentiment expressed by these words has come to vex evolutionary biologists. "This belief," Richard Dawkins writes, "that Darwinian evolution is 'random,' is not merely false. It is the exact opposite of the truth." But Monod is right and Dawkins wrong. Chance lies at the beating heart of evolutionary theory, just as it lies at the beating heart of thermodynamics.

It is the second law of thermodynamics that holds dominion over the temporal organization of the universe, and what the law has to say we find verified by ordinary experience at every turn. Things fall apart. Energy, like talent, tends to squander itself. Liquids go from hot to lukewarm. And so does love. Disorder and despair overwhelm the human enterprise, filling our rooms and our lives with clutter. Decay is unyielding. Things go from bad to worse. And overall, they go *only* from bad to worse.

These grim certainties the second law abbreviates in the solemn and awful declaration that the entropy of the universe is tending toward a maximum. The final state in which entropy is maximized is simply more *likely* than any other state. The disintegration of my face reflects nothing more compelling than the odds. Sheer dumb luck.

But if things fall apart, they also come together. *Life* appears to offer at least a temporary rebuke to the second law of thermodynamics. Although biologists are unanimous in arguing that evolution has no goal, fixed from the first, it remains true nonetheless that living creatures have organized themselves into ever more elaborate and flexible structures. If their complexity is increasing, the entropy that surrounds them is decreasing. Whatever the universe-as-a-whole may be doing—time fusing incomprehensibly with space, the great stars exploding indignantly—biologically things have gone from bad to *better*, the show organized, or so it would seem, as a counterexample to the prevailing winds of fate.

How so? The question has historically been the pivot on which the assumption of religious belief has turned. How so? "God said: 'Let the waters swarm with swarms of living creatures, and let fowl fly above the earth in the open firmament of heaven.'" That is how so. And who on the basis of experience would be inclined to disagree? The structures of life are complex, and complex structures get made in this, the purely human world, only by a process of deliberate design. An act of intelligence is required to bring even a thimble into being; why should the artifacts of life be different?

Darwin's theory of evolution rejects this counsel of experience and intuition. Instead, the theory forges, at least in spirit, a perverse connection with the second law itself, arguing that precisely the same force that explains one turn of the cosmic wheel explains another: sheer dumb luck.

If the universe is for reasons of sheer dumb luck committed ultimately to a state of cosmic listlessness, it is *also* by sheer dumb luck that life first emerged on earth, the chemicals in the pre-biotic seas or soup illuminated and then invigorated by a fateful flash of lightning. It is again by sheer dumb luck that the first self-reproducing systems were created. The dense and ropy chains of RNA—they were created by sheer dumb luck, and sheer dumb luck drove the primitive chemicals of life to form a living cell. It is sheer dumb luck that alters the genetic message so that, from infernal nonsense, meaning for a moment emerges; and sheer dumb

luck again that endows life with its *opportunities*, the space of possibilities over which natural selection plays, sheer dumb luck creating the mammalian eye and the marsupial pouch, sheer dumb luck again endowing the elephant's sensitive nose with nerves and the orchid's translucent petal with blush.

Amazing. Sheer dumb luck.

### *Life, Complex Life*

**P**HYSICISTS ARE persuaded that things are in the end simple; biologists that they are not. A good deal depends on where one looks. Wherever the biologist looks, there is complexity beyond complexity, the entanglement of things ramifying downward from the organism to the cell. In a superbly elaborated figure, the Australian biologist Michael Denton compares a single cell to an immense automated factory, one the size of a large city:

On the surface of the cell we would see millions of openings, like the portholes of a vast space ship, opening and closing to allow a continual stream of materials to flow in and out. If we were to enter one of these openings we would find ourselves in a world of supreme technology and bewildering complexity. We would see endless highly organized corridors and conduits branching in every direction away from the perimeter of the cell, some leading to the central memory bank in the nucleus and others to assembly plants and processing units. The nucleus itself would be a vast spherical chamber more than a kilometer in diameter, resembling a geodesic dome inside of which we would see, all neatly stacked together in ordered arrays, the miles of coiled chains of the DNA molecule. . . . We would notice that the simplest of the functional components of the cell, the protein molecules, were, astonishingly, complex pieces of molecular machinery. . . . Yet the life of the cell depends on the integrated activities of thousands, certainly tens, and probably hundreds of thousands of different protein molecules.

And whatever the complexity of the cell, it is insignificant in comparison with the mammalian nervous system; and beyond that, far impossibly ahead, there is the human mind, an instrument like no other in the biological world, conscious, flexible, penetrating, inscrutable, and profound.

It is here that the door of doubt begins to swing. *Chance* and *complexity* are countervailing forces; they work at cross-purposes. This circumstance the English theologian William Paley (1743-1805)

made the gravamen of his well-known argument from design:

Nor would any man in his senses think the existence of the watch, with its various machinery, accounted for, by being told that it was one out of possible combinations of material forms; that whatever he had found in the place where he found the watch, must have contained some internal configuration or other, and that this configuration might be the structure now exhibited, viz., of the works of a watch, as well as a different structure.

It is worth remarking, it is simply a *fact*, that this courtly and old-fashioned argument is entirely compelling. We *never* attribute the existence of a complex artifact to chance. And for obvious reasons: complex objects are useful islands, isolated amid an archipelago of useless possibilities. Of the thousands of ways in which a watch might be assembled from its constituents, only one is liable to work. It is unreasonable to attribute the existence of a watch to chance, if only because it is *unlikely*. An artifact is the overflow in matter of the mental motions of intention, deliberate design, planning, and coordination. The inferential spool runs backward, and it runs irresistibly from a complex object to the contrived, the artificial, circumstances that brought it into being.

Paley allowed the conclusion of his argument to drift from man-made to biological artifacts, a human eye or kidney falling under the same classification as a watch. "Every indication of contrivance," he wrote, "every manifestation of design, exists in the works of nature; with the difference, on the side of nature, of being greater or more, and that in a degree which exceeds all computation."

In this drifting, Darwinists see dangerous signs of a non sequitur. There is a tight connection, they acknowledge, between what a watch is and how it is made; but the connection unravels at the human eye—or any other organ, disposition, body plan, or strategy—if only because another and a simpler explanation is available. Among living creatures, say Darwinists, *the design persists even as the designer disappears*.

"Paley's argument," Dawkins writes, "is made with passionate sincerity and is informed by the best biological scholarship of his day, but it is wrong, gloriously and utterly wrong."

The enormous confidence this quotation expresses must be juxtaposed against the weight of intuition it displaces. It is true that intuition is often wrong—quantum theory is intuition's grave-

yard. But quantum theory is remote from experience; our intuitions in biology lie closer to the bone. We are ourselves such stuff as genes are made on, and while this does not establish that our assessments of time and chance must be correct, it does suggest that they may be pertinent.

### *The Book of Life*

THE DISCOVERY of DNA by James D. Watson and Francis Crick in 1952 revealed that a living creature is an organization of matter orchestrated by a genetic text. Within the bacterial cell, for example, the book of life is written in a distinctive language. The book is read aloud, its message specifying the construction of the cell's constituents, and then the book is copied, passed faithfully into the future.

This striking metaphor introduces a troubling instability, a kind of tremor, into biological thought. With the discovery of the genetic code, every living creature comes to divide itself into alien realms: the alphabetic and the organic. The realms are conceptually distinct, responding to entirely different imperatives and constraints. An alphabet, on the one hand, belongs to the class of finite combinatorial objects, things that are discrete and that fit together in highly circumscribed ways. An organism, on the other hand, traces a continuous figure in space and in time. How, then, are these realms coordinated?

I ask the question because in similar systems, coordination is crucial. When I use the English language, the rules of grammar act as a constraint on the changes that I might make to the letters or sounds I employ. This is something we take for granted, an ordinary miracle in which I pass from one sentence to the next, almost as if crossing an abyss by means of a series of well-placed stepping stones.

In living creatures, things evidently proceed otherwise. There is *no* obvious coordination between alphabet and organism; the two objects are governed by different conceptual regimes, and that apparently is the end of it. Under the pressures of competition, the orchid *Orchis apifera* undergoes a statistically adapted drift, some incidental feature in its design becoming over time ever more refined, until, consumed with longing, a misguided bee amorously mounts the orchid's very petals, convinced that he has seen shimmering there a female's fragile genitalia. As this is taking place, the marvelous mimetic design maturing slowly, the orchid's underlying alphabetic system

undergoes a series of *random* perturbations, letters in its genetic alphabet winking off or winking on in a way utterly independent of the grand convergent progression toward perfection taking place out there where the action is.

We do not understand, we cannot re-create, a system of this sort. However it may operate in life, randomness in language is the enemy of order, a way of annihilating meaning. And not only in language, but in any language-*like* system—computer programs, for example. The alien influence of randomness in such systems was first noted by the distinguished French mathematician M.P. Schützenberger, who also marked the significance of this circumstance for evolutionary theory. "If we try to simulate such a situation," he wrote, "by making changes randomly . . . on computer programs, we find that we have no chance . . . even to see what the modified program would compute; it just jams."<sup>3</sup>

### *Planets of Possibility*

THIS IS not yet an argument, only an expression of intellectual unease; but the unease tends to build as analogies are amplified. The general issue is one of size and space, and the way in which something small may be found amidst something very big.

Linguists in the 1950's, most notably Noam Chomsky and George Miller, asked dramatically how many grammatical English sentences could be constructed with 100 letters. Approximately 10 to the 25th power ( $10^{25}$ ), they answered. This is a very large number. But a sentence is one thing; a sequence, another. A sentence obeys the laws of English grammar; a sequence is lawless and comprises *any* concatenation of those 100 letters. If there are roughly ( $10^{25}$ ) sentences at hand, the number of sequences 100 letters in length is, by way of contrast, 26 to the 100th power ( $26^{100}$ ). This is an inconceivably greater number. The space of possibilities has blown up, the explosive process being one of *combinatorial inflation*.

Now, the vast majority of sequences drawn on a finite alphabet fail to make a statement: they consist of letters arranged to no point or purpose. It is the contrast between sentences and sequences that

<sup>3</sup> Schützenberger's comments were made at a symposium held in 1966. The proceedings were edited by Paul S. Moorhead and Martin Kaplan and published as *Mathematical Challenges to the Neo-Darwinian Interpretation of Evolution* (Wistar Institute Press, 1967). Schützenberger's remarks, together with those of the physicist Murray Eden at the same symposium, constituted the first significant criticism of evolutionary doctrine in recent decades.

carries the full, critical weight of memory and intuition. Organized as a writhing ball, the sequences resemble a planet-sized object, one as large as pale Pluto. Landing almost anywhere on that planet, linguists see nothing but nonsense. Meaning resides with the grammatical sequences, but they, those *sentences*, occupy an area no larger than a dime.

How on earth could the sentences be *discovered by chance* amid such an infernal and hyperborean immensity of gibberish? They cannot be discovered by chance, and, of course, chance plays no role in their discovery. The linguist or the native English-speaker moves around the place or planet with a perfectly secure sense of where he should go, and what he is apt to see.

The eerie and unexpected presence of an alphabet in every living creature might suggest the possibility of a similar argument in biology. It is DNA, of course, that acts as life's primordial text, the code itself organized in nucleic triplets, like messages in Morse code. Each triplet is matched to a particular chemical object, an amino acid. There are twenty such acids in all. They correspond to letters in an alphabet. As the code is read somewhere in life's hidden housing, the linear order of the nucleic acids induces a corresponding linear order in the amino acids. The biological finger writes, and what the cell reads is an ordered presentation of such amino acids—a protein.

Like the nucleic acids, proteins are alphabetic objects, composed of discrete constituents. On average, proteins are roughly 250 amino acid residues in length, so a given protein may be imagined as a long biochemical word, one of many.

The aspects of an analogy are now in place. What is needed is a relevant contrast, something comparable to sentences and sequences in language. Of course nothing completely comparable is at hand: there are *no* sentences in molecular biology. Nonetheless, there is this fact, helpfully recounted by Richard Dawkins: "The actual animals that have ever lived on earth are a tiny subset of the theoretical animals that *could* exist." It follows that over the course of four billion years, life has expressed itself by means of a particular stock of proteins, a certain set of life-like words.

**A** COMBINATORIAL COUNT is now possible. The MIT physicist Murray Eden, to whom I owe this argument, estimates the number of the viable proteins at 10 to the 50th power ( $10^{50}$ ). Within this set is the raw material of everything that has ever lived: the flowering plants and the

alien insects and the seagoing turtles and the sad shambling dinosaurs, the great evolutionary successes and the great evolutionary failures as well. These creatures are, quite literally, composed of the proteins that over the course of time have performed some useful function, with "usefulness" now standing for the sense of sentencehood in linguistics.

As in the case of language, what has once lived occupies some corner in the space of a larger array of possibilities, the actual residing in the shadow of the possible. The space of all *possible* proteins of a fixed length (250 residues, recall) is computed by multiplying 20 by itself 250 times ( $20^{250}$ ). It is idle to carry out the calculation. The number is larger by far than seconds in the history of the world since the Big Bang or grains of sand on the shores of every sounding sea. Another planet now looms in the night sky, Pluto-sized or bigger, a conceptual companion to the planet containing every sequence composed by endlessly arranging the 26 English letters into sequences 100 letters in length. This planetary *doppelgänger* is the planet of all possible proteins of fixed length, the planet, in a certain sense, of every *conceivable* form of carbon-based life.

And there the two planets lie, spinning on their soundless axes. The contrast between sentences and sequences on Pluto reappears on Pluto's double as the contrast between useful protein forms and all the rest; and it reappears in terms of the same dramatic difference in numbers, the enormous ( $20^{250}$ ) overshadowing the merely big ( $10^{50}$ ), the contrast between the two being quite literally between an immense and swollen planet and a dime's worth of area. That dime-sized corner, which on Pluto contains the English sentences, on Pluto's double contains the living creatures; and there the biologist may be seen tramping, the warm puddle of wet life achingly distinct amid the planet's snow and stray proteins. It is here that living creatures, whatever their ultimate fate, breathed and moaned and carried on, life evidently having discovered the small quiet corner of the space of possibilities in which things *work*.

It would seem that evolution, Murray Eden writes in artfully ambiguous language, "was directed toward the incredibly small proportion of useful protein forms. . . ." the word "directed" conveying, at least to me, the sobering image of a stage-managed search, with evolution bypassing the awful immensity of all that frozen space because in some sense evolution *knew* where it was going.

And yet, from the perspective of Darwinian the-

ory, it is chance that plays the crucial—that plays the *only*—role in generating the proteins. Wandering the surface of a planet, evolution wanders blindly, having forgotten where it has been, unsure of where it is going.

### *The Artificer of Design*

RANDOM MUTATIONS are the great creative demiurge of evolution, throwing up possibilities and bathing life in the bright light of chance. Each living creature is not only what it is but what it might be. What, then, acts to make the possible palpable?

The theory of evolution is a materialistic theory. Various deities need not apply. Any form of mind is out. Yet a force is needed, something adequate to the manifest complexity of the biological world, and something that in the largest arena of all might substitute for the acts of design, anticipation, and memory that are obvious features of such day-to-day activities as fashioning a sentence or a sonnet.

This need is met in evolutionary theory by natural selection, the filter but not the source of change. "It may be said," Darwin wrote,

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 insensibly working, whenever and wherever opportunity offers, as the improvement of each organic being in relation to its organic and inorganic conditions of life.

Natural selection emerges from these reflections as a strange force-like concept. It is strange because it is unconnected to any notion of force in physics, and it is force-*like* because natural selection *does* something, it has an effect and so functions as a kind of cause.<sup>4</sup> Creatures, habits, organ systems, body plans, organs, and tissues are *shaped* by natural selection. Population geneticists write of selection forces, selection pressures, and coefficients of natural selection; biologists say that natural selection sculpts, shapes, coordinates, transforms, directs, controls, changes, and transfigures living creatures.

It is natural selection, Richard Dawkins believes, that is the artificer of design, a cunning force that mocks human ingenuity even as it mimics it:

Charles Darwin showed how it is possible for blind physical forces to mimic the effects of conscious design, and, by operating as a cumu-

lative filter of chance variations, to lead eventually to organized and adaptive complexity, to mosquitoes and mammoths, to humans and therefore, indirectly, to books and computers.

In affirming what Darwin showed, these words suggest that Darwin demonstrated the power of natural selection in some formal sense, settling the issue once and for all. But that is simply not true. When Darwin wrote, the mechanism of evolution that he proposed had only life itself to commend it. But to refer to the power of natural selection by appealing to the course of evolution is a little like confirming a story in the *New York Times* by reading it twice. The theory of evolution is, after all, a general theory of change; if natural selection can sift the debris of chance to fashion an elephant's trunk, should it not be able to work elsewhere—amid computer programs and algorithms, words and sentences? Skeptics require a demonstration of natural selection's cunning, one that does not involve the very phenomenon it is meant to explain.

No sooner said than done. An extensive literature is now devoted to what is optimistically called artificial life. These are schemes in which a variety of programs generate amusing computer objects and by a process said to be similar to evolution show that they are capable of growth and decay and even a phosphorescent simulacrum of death. An algorithm called "Face Prints," for example, has been designed to enable crime victims to identify their attackers. The algorithm runs through hundreds of facial combinations (long hair, short hair, big nose, wide chin, moles, warts, wens, wrinkles) until the indignant victim spots the resemblance between the long-haired, big-nosed, wide-chinned portrait of the perpetrator and the perpetrator himself.

It is the presence of the *human* victim in this scenario that should give pause. What is *he* doing there, complaining loudly amid those otherwise blind forces? A mechanism that requires a discerning human agent cannot be Darwinian. The Darwinian mechanism neither anticipates nor remembers. It gives no directions and makes no choices. What is unacceptable in evolutionary theory, what is strictly forbidden, is the appearance of a force with the power to survey time, a force that con-

<sup>4</sup> Murray Eden is, as usual, perceptive: "It is as if," he writes, "some pre-Newtonian cosmologist had proposed a theory of planetary motion which supposed that a natural force of unknown origin held the planets in their courses. The supposition is right enough and the idea of a force between two celestial bodies is a very useful one, but it is hardly a theory."

serves a point or a property because it *will* be useful. Such a force is no longer Darwinian. How would a blind force know such a thing? And by what means could future usefulness be transmitted to the present?

If life is, as evolutionary biologists so often say, a matter merely of blind thrusting and throbbing, any definition of natural selection must plainly meet what I have elsewhere called a rule against deferred success.<sup>5</sup> It is a rule that cannot be violated with impunity; if evolutionary theory is to retain its intellectual integrity, it cannot be violated at all.

But the rule is widely violated, the violations so frequent as to amount to a formal fallacy.

### *Advent of the Head Monkey*

IT IS Richard Dawkins's grand intention in *The Blind Watchmaker* to demonstrate, as one reviewer enthusiastically remarked, "how natural selection allows biologists to dispense with such notions as purpose and design." This he does by exhibiting a process in which the random exploration of certain possibilities, a *blind stab* here, another there, is followed by the filtering effects of natural selection, some of those stabs saved, others discarded. But could a process so conceived—a *Darwinian* process—discover a simple English sentence: a target, say, chosen from Shakespeare? The question is by no means academic. If natural selection cannot discern a simple English sentence, what chance is there that it might have discovered the mammalian eye or the system by which glucose is regulated by the liver?

A thought experiment in *The Blind Watchmaker* now follows. Randomness in the experiment is conveyed by the metaphor of the monkeys, perennial favorites in the theory of probability. There they sit, simian hands curved over the keyboards of a thousand typewriters, their long agile fingers striking keys at random. It is an image of some poignancy, those otherwise intelligent apes banging away at a machine they cannot fathom; and what makes the poignancy pointed is the fact that the system of rewards by which the apes have been induced to strike the typewriter's keys is from the first rigged against them.

The probability that a monkey will strike a given letter is one in 26. The typewriter has 26 keys: the monkey, one working finger. But a letter is not a word. Should Dawkins demand that the monkey get two English letters right, the odds against success rise with terrible inexorability from one in 26 to one in 676. The Shakespearean target

chosen by Dawkins—"Methinks it is like a weasel"—is a six-word sentence containing 28 English letters (including the spaces). It occupies an isolated point in a space of 10,000 million, million, million, million, million, million possibilities.

This is a very large number; combinatorial inflation is at work. And these are very long odds. And a six-word sentence consisting of 28 English letters is a very short, very simple English sentence.

Such are the fatal facts. The problem confronting the monkeys is, of course, a double one: they must, to be sure, find the right letters, but they cannot *lose* the right letters once they have found them. A random search in a space of this size is an exercise in irrelevance. This is something the monkeys appear to know.

What more, then, is expected; what more required? *Cumulative* selection, Dawkins argues—the answer offered as well by Stephen Jay Gould, Manfred Eigen, and Daniel Dennett. The experiment now proceeds in stages. The monkeys type randomly. After a time, they are allowed to survey what they have typed in order to choose the result "which *however slightly* most resembles the target phrase." It is a computer that in Dawkins's experiment performs the crucial assessments, but I prefer to imagine its role assigned to a scrutinizing monkey—the Head Monkey of the experiment. The process under way is one in which stray successes are spotted and then saved. This process is iterated and iterated again. Variations close to the target are conserved *because* they are close to the target, the Head Monkey equably surveying the scene until, with the appearance of a miracle in progress, randomly derived sentences do begin to converge on the target sentence itself.

The contrast between schemes and scenarios is striking. Acting on their own, the monkeys are adrift in fathomless possibilities, any accidental success—a pair of English-like letters—lost at once, those successes seeming like faint untraceable lights flickering over a wine-dark sea. The advent of the Head Monkey changes things entirely. Successes are *conserved* and then conserved again. The light that formerly flickered uncertainly now stays lit, a beacon burning steadily, a point of illumination. By the light of that light, other lights are lit, until the isolated successes converge, bringing order out of nothingness.

The entire exercise is, however, an achievement in self-deception. A *target* phrase? Iterations that *most resemble* the target? A Head Monkey that *mea-*

<sup>5</sup> *Black Mischief: Language, Life, Logic & Luck* (1986).

sures the distance between failure and success? If things are sightless, how is the target represented, and how is the distance between randomly generated phrases and the targets assessed? And by whom? And the Head Monkey? What of him? The mechanism of deliberate design, purged by Darwinian theory on the level of the organism, has reappeared in the description of natural selection itself, a vivid example of what Freud meant by the return of the repressed.

This is a point that Dawkins accepts without quite acknowledging, rather like a man adroitly separating his doctor's diagnosis from his own disease.<sup>6</sup> Nature presents life with no targets. Life shambles forward, surging here, shuffling there, the small advantages accumulating *on their own* until something novel appears on the broad evolutionary screen—an arch or an eye, an intricate pattern of behavior, the complexity characteristic of life. May we, then, see *this* process at work, by seeing it simulated? "Unfortunately," Dawkins writes, "I think it may be beyond my powers as a programmer to set up such a counterfeit world."<sup>7</sup>

This is the authentic voice of contemporary Darwinian theory. What may be illustrated by the theory does not involve a Darwinian mechanism; what involves a Darwinian mechanism cannot be illustrated by the theory.

### *Darwin Without Darwinism*

BIOLOGISTS OFTEN affirm that as members of the scientific community they positively welcome criticism. Nonsense. Like everyone else, biologists loathe criticism and arrange their lives so as to avoid it. Criticism has nonetheless seeped into their souls, the process of doubt a curiously Darwinian one in which individual biologists entertain minor reservations about their theory without ever recognizing the degree to which these doubts mount up to a substantial deficit. Creationism, so often the target of their indignation, is the least of their worries.

For many years, biologists have succeeded in keeping skepticism on the circumference of evolutionary thought, where paleontologists, taxonomists, and philosophers linger. But the burning fringe of criticism is now contracting, coming ever closer to the heart of Darwin's doctrine. In a paper of historic importance, Stephen Jay Gould and Richard Lewontin expressed their dissatisfaction with what they termed "just-so" stories in biology.<sup>8</sup> It is by means of a just-so story, for example, that the pop biologist Elaine Morgan explains the

presence in human beings of an aquatic diving reflex. An obscure primate ancestral to man, Morgan argues, was actually aquatic, having returned to the sea like the dolphin. Some time later, that primate, having tired of the water, clambered back to land, his aquatic adaptations intact. Just so.

If stories of this sort are intellectually inadequate—preposterous, in fact—some biologists are prepared to argue that they are unnecessary as well, another matter entirely. "How seriously," H. Allen Orr asked in a superb if savage review of Dennett's *Darwin's Dangerous Idea*,

should we take these endless adaptive explanations of features whose alleged Design may be illusory? Isn't there a difference between those cases where we recognize Design *before* we understand its precise significance and those cases where we try to make Design manifest by concocting a story? And isn't it especially worrisome that we can make up arbitrary traits faster than adaptive stories, and adaptive stories faster than experimental tests?

The camel's lowly hump and the elephant's nose—*these*, Orr suggests, may well be adaptive and so designed by natural selection. But beyond the old familiar cases, life may not be designed at all, the weight of evolution borne by neutral mutations, with genes undergoing a slow but pointless drifting in time's soft currents.

Like Orr, many biologists see an acknowledgment of their doubts as a cagey, a *calculated*, concession; but cagey or not, it is a concession devastating to the larger project of Darwinian biology. Unable to say *what* evolution has accomplished, biologists now find themselves unable to say *whether* evolution has accomplished it. This leaves evolutionary theory in the doubly damned position of having compromised the concepts needed to make sense of life—complexity, adaptation, design—while simultaneously conceding that the theory does little to explain them.

<sup>6</sup> The same pattern of intellectual displacement is especially vivid in Daniel Dennett's description of natural selection as a force subordinate to what he calls "the principle of the accumulation of design." Sifting through the debris of chance, natural selection, he writes, occupies itself by "thriflily conserving the design work . . . accomplished at each stage." But there is *no* such principle. Dennett has simply assumed that a sequence of conserved advantages will converge to an improvement in design; the assumption expresses a non sequitur.

<sup>7</sup> It is absurdly easy to set up a sentence-searching algorithm obeying purely Darwinian constraints. The result, however, is always the same—gibberish.

<sup>8</sup> "The Spandrels of San Marco and the Panglossian Paradigm: A Critique of the Adaptationist Programme," *Proceedings of the Royal Society, Volume B* 205 (1979).

No DOUBT, the theory of evolution will continue to play the singular role in the life of our secular culture that it has always played. The theory is unique among scientific instruments in being cherished not for what it contains, but for what it lacks. There are in Darwin's scheme no biotic laws, no *Bauplan* as in German natural philosophy, no special creation, no *élan vital*, no divine guidance or transcendental forces. The theory functions simply as a description of matter in one of its modes, and

living creatures are said to be something that the gods of law indifferently sanction and allow.

"Darwin," Richard Dawkins has remarked with evident gratitude, "made it possible to be an intellectually fulfilled atheist." This is an exaggeration, of course, but one containing a portion of the truth. That Darwin's theory of evolution and biblical accounts of creation play similar roles in the human economy of belief is an irony appreciated by altogether too few biologists.

## On the Derivation of *Ulysses* from *Don Quixote*

**I**MAGINE THIS story being told to me by Jorge Luis Borges one evening in a Buenos Aires café.

His voice dry and infinitely ironic, the aging, nearly blind literary master observes that "the *Ulysses*," mistakenly attributed to the Irishman James Joyce, is in fact derived from "the *Quixote*."

I raise my eyebrows.

Borges pauses to sip discreetly at the bitter coffee our waiter has placed in front of him, guiding his hands to the saucer.

"The details of the remarkable series of events in question may be found at the University of Leiden," he says. "They were conveyed to me by the Freemason Alejandro Ferri in Montevideo."

Borges wipes his thin lips with a linen handkerchief that he has withdrawn from his breast pocket.

"As you know," he continues, "the original handwritten text of the *Quixote* was given to an order of French Cistercians in the autumn of 1576."

I hold up my hand to signify to our waiter that no further service is needed.

"Curiously enough, for none of the brothers could read Spanish, the Order was charged by the Papal

Nuncio, Hoyo dos Monterrey (a man of great refinement and implacable will), with the responsibility for copying the *Quixote*, the printing press having then gained no currency in the wilderness of what is now known as the department of Auvergne. Unable to speak or read Spanish, a language they not unreasonably detested, the brothers copied the *Quixote* over and over again, re-creating the text but, of course, compromising it as well, and so inadvertently discovering the true nature of authorship. Thus they created Fernando Lor's *Los Hombres d'Estado* in 1585 by means of a singular series of copying errors, and then in 1654 Juan Luis Samorza's remarkable epistolary novel *Por Favor* by the same means, and then in 1685, the errors having accumulated sufficiently to change Spanish into French, Molière's *Le Bourgeois Gentilhomme*, their copying continuous and indefatigable, the work handed down from generation to generation as a sacred but secret trust, so that in time the brothers of the monastery, known only to members of the Bourbon house and, rumor has it, the Englishman and psychic Conan Doyle, copied into creation Stend-

hal's *The Red and the Black* and Flaubert's *Madame Bovary*, and then as a result of a particularly significant series of errors, in which French changed into Russian, Tolstoy's *The Death of Ivan Ilyich* and *Anna Karenina*. Late in the last decade of the 19th century there suddenly emerged, in English, Oscar Wilde's *The Importance of Being Earnest*, and then the brothers, their numbers reduced by an infectious disease of mysterious origin, finally copied the *Ulysses* into creation in 1902, the manuscript lying neglected for almost thirteen years and then mysteriously making its way to Paris in 1915, just months before the British attack on the Somme, a circumstance whose significance remains to be determined."

I sit there, amazed at what Borges has recounted. "Is it your understanding, then," I ask, "that every novel in the West was created in this way?"

"Of course," replies Borges imperturbably. Then he adds: "Although every novel is derived directly from another novel, there is really only one novel, the *Quixote*."

— D.B.

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# A Scientific Scandal

*David Berlinski*

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**I**N SCIENCE, as in life, it is always an excellent idea to cut the cards after the deck has been shuffled. One may admire the dealer, but trust is another matter.

In a recent essay in *COMMENTARY*, “Has Darwin Met His Match?” (December 2002), I discussed, evaluated, and criticized theories of intelligent design, which have presented the latest challenge to Darwin’s theory of evolution. In the course of the discussion I observed that the evolution of the mammalian eye has always seemed difficult to imagine. It is an issue that Darwin himself raised, and although he settled the matter to his own satisfaction, biologists have long wished for a *direct* demonstration that something like a functional eye could be formed in reasonable periods of time by means of the Darwinian principles of random variation and natural selection.

Just such a demonstration, I noted in my essay, is what the biologists Dan-Erik Nilsson and Susanne Pelger seemed to provide in a 1994 paper.<sup>1</sup> Given nothing more than time and chance, a “light-sensitive patch,” they affirmed, *can* “gradually turn into a focused-lens eye,” and in the space of only a few hundred thousand years—a mere moment, as such things go.

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Nilsson and Pelger’s paper has, for understandable reasons, been widely circulated and widely praised, and in the literature of evolutionary biology it is now regularly cited as definitive. Not the least of its remarkable authority is derived from the belief that it contains, in the words of one of its defenders, a “computer simulation of the eye’s evolution.”

If this were true, it would provide an extremely important defense of Darwin’s theory. Although a computer simulation is not by itself conclusive—a simulation is one thing, reality another—it is often an important link in an inferential chain. In the case of Darwin’s theory, the matter is especially pressing since in the nature of things the theory cannot be confirmed over geological time by any experimental procedure, and it has proved very difficult to confirm under laboratory conditions. The claim that the eye’s evolution has been successfully simulated by means of Darwinian principles, with results falling well within time scales required by the theory, is thus a matter of exceptional scientific importance.

And not just *scientific* importance, I might add; so dramatic a confirmation of Darwinian theory carries large implications for our understanding of the human species and its origins. This is no doubt

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<sup>1</sup> “A Pessimistic Estimate of the Time Required for an Eye to Evolve,” *Proceedings of the Royal Society, London B* (1994) 256, 53–58. In my essay I twice misspelled Susanne Pelger’s name, for which I apologize.

why the story of Nilsson and Pelger's computer simulation has spread throughout the world. Their study has been cited in essays, textbooks, and popular treatments of Darwinism like *River Out of Eden* by the famous Oxford evolutionist Richard Dawkins; accounts of it have made their way onto the Internet in several languages; it has been promoted to the status of a certainty and reported as fact in the press, where it is inevitably used to champion and vindicate Darwin's theory of evolution.

In my essay, I suggested that Nilsson and Pelger's arguments are trivial and their conclusions unsubstantiated. I also claimed that representations of their paper by the scientific community have involved a serious, indeed a flagrant, distortion of their work. But in a letter published in the March issue of *COMMENTARY*, the physicist Matt Young, whom I singled out for criticism (and whose words I have quoted here), repeated and defended his characterization of Nilsson and Pelger's work as a "computer simulation of the eye's evolution." It is therefore necessary to set the matter straight in some detail.

I hope this exercise will help to reveal, with a certain uncomfortable clarity, just how scientific orthodoxy works, and how it imposes its opinions on the faithful.

**H**ERE IN their own words is the main argument of Nilsson and Pelger's paper:

Theoretical considerations of eye design allow us to find routes along which the optical structure of the eye may have evolved. If selection constantly favors an increase in the amount of detectable spatial information, a light-sensitive patch will gradually turn into a focused-lens eye through continuous small improvements in design. An upper limit for the number of generations required for the complete transformation can be calculated with a minimum number of assumptions. Even with a consistently pessimistic approach, the time required becomes amazingly short: only a few hundred thousand years.

And here is how they arrived at their conclusions. The setting is "a single circular patch of light-sensitive cells"—a retina, in effect—"which is bracketed and surrounded by dark pigment." A "protective layer" lies above these light-sensitive cells, so that the pigment, the light-sensitive cells, and the protective layer form a kind of sandwich. Concerning the light-sensitive patch itself, Nilsson and Pelger provide no further details, indicating neither its size nor the number of cells it might contain.

What they do assume, if only implicitly, is that changes to the initial patch involve either a deformation of its shape or a thickening of its cells. The patch can be stretched, dimpled, and pulled or pushed around, and cells may move closer to one another, like bond salesmen converging on a customer.

So much for what changes. What is the change worth? Assuming (reasonably enough) that an eye is an organ used in order to see, Nilsson and Pelger represent its value to an organism by a single quantitative character or function, which they designate as "spatial resolution" or "visual acuity"—sharp sight, in short. Visual acuity confers an advantage on an organism, and so, in any generation, natural selection "constantly favors an increase in the amount of detectable spatial information."

There are two ways in which visual acuity may be increased in an initial light-sensitive patch: a) by the "invagination" of the patch, so that it becomes progressively more concave and eventually forms the enclosed interior of a sphere; and b) by the constriction of the sphere's aperture (the two rounded boundaries formed as the flat patch undergoes invagination). These changes may be represented on sheets of high-school graph paper on which two straight lines—the *x* and *y* axes of the system—have been crossed. On the first sheet, representing invagination, visual acuity moves upward on one axis as invagination moves to the right on the other; on the second sheet, visual acuity moves upward as constriction moves to the right. The curves that result, Nilsson and Pelger assert, are continuous and increasing. They do not hurdle over any gaps, and they go steadily upward until they reach a theoretical maximum.

The similar shape of the two graphs notwithstanding, invagination and aperture constriction exercise different effects on visual acuity. "Initially, deepening of the pit"—i.e., invagination—"is by far the most efficient strategy," Nilsson and Pelger write; "but when the pit depth equals the width, aperture constriction becomes more efficient than continued deepening of the pit." From this, they conclude that natural selection would act "first to favor depression and invagination of the light-sensitive patch, and then gradually change to favor constriction of the aperture."

**T**HE RESULT is a pin-hole eye, which is surely an improvement on no eye at all. But there exists an aperture size beyond which visual acuity cannot be improved without the introduction of a lens. Having done all that it can do, the pin-hole eye lapses. Cells within the light-sensitive sphere now oblig-

ingly begin to thicken themselves, bringing about a "local increase" in the eye's refractive index and so forming a lens. When the focal length of the lens is 2.55 times its radius—the so-called Mattiesen ratio—the eye will have achieved, Nilsson and Pelger write, the "ideal solution for a graded-index lens with a central refractive index of 1.52."<sup>2</sup>

Thereafter, the lens "changes its shape from ellipsoid to spherical and moves to the center of curvature of the retina." A flat iris "gradually forms by stretching of the original aperture," while the "focal length of the lens . . . gradually shortens, [until] it equals the distance to the retina . . . producing a sharply focused image." The appearance of this spherical, graded-index lens, when placed in the center of curvature of the retina, produces "virtually aberration-free imaging over the full 180 degrees of the visual field."

The same assumptions that governed invagination and aperture constriction hold sway here as well. Plotted against increasing lens formation, visual acuity moves smoothly and steadily upward as a graded-index lens makes its appearance, changes its shape, and moves to center stage. When these transformations have been completed, the result is a "focused camera-type eye with the geometry typical for aquatic animals."

One step remains. Nilsson and Pelger now amalgamate invagination, constriction, and lens formation into a single "transformation," which they represent by juxtaposing, against changes in visual acuity, changes to the original patch in increments of 1 percent. The resulting curve, specifying quantitatively how much visual acuity may be purchased for each 1-percent unit of change, is ascending, increasing, and straight, rising like an arrow at an angle of roughly 45 degrees from its point of origin. Transformations are "optimal" in the sense that they bring about as much visual acuity as theoretically possible, with the "geometry of each stage [setting] an upper limit to the spatial resolution of the eye."

It is the existence and shape of this fourth curve that justify their claim that "a light-sensitive patch will gradually turn into a focused-lens eye through continuous small improvements in *design*" (emphasis added). This is not the happiest formulation they could have chosen.

**H**OW MUCH does the initial light-sensitive patch have to change in order to realize a focused camera-type eye? And how long will it take to do so? These are the questions now before us.

As I have mentioned, Nilsson and Pelger assume

that their initial light-sensitive patch changes in 1-percent steps. They illustrate the procedure with the example of a flat one-foot ruler that also changes in 1-percent steps. After the first step, the ruler will be one foot plus 1 percent of one foot long; after the second step, it will be 1-percent longer than the length just achieved; and so forth. It requires roughly 70 steps to double a one-foot ruler in length. Putting the matter into symbols,  $1.01^{70} \approx 2$ .

Nilsson and Pelger undertake a very similar calculation with respect to their initial light-sensitive patch. But since the patch is a three-dimensional object, they are obliged to deal with three dimensions of change. Growing in steps of 1 percent, their blob increases its length, its curvature, and its volume. When all of these changes are shoehorned together, the patch will have increased in magnitude along some overall (but unspecified) dimension.

The chief claim of their paper now follows: to achieve the visual acuity that is characteristic of a "focused camera-type eye with the geometry typical for aquatic animals," it is necessary that an initial patch be made 80,129,540 times larger (or greater or grander) than it originally was. This number represents the *magnitude* of the blob's increase in size. How many *steps* does that figure represent? Since  $80,129,540 = 1.01^{1,829}$ , Nilsson and Pelger conclude that "altogether 1,829 steps of 1 percent are required" to bring about the requisite transformation.

These steps, it is important to remember, do not represent *temporal* intervals. We still need to assess how rapidly the advantages represented by such a transformation would spread in a population of organisms, and so answer the question of how long the process takes. In order to do this, Nilsson and Pelger turn to population genetics. The equation that follows involves the multiplication of four numbers:

$$R = h^2 \times i \times V \times m$$

Here,  $R$  is the response (i.e. visual acuity in each generation),  $h$  is the coefficient of heredity,  $i$  designates the intensity of selection,  $V$  is the coefficient of variation (the ratio of the standard deviation to the mean), and  $m$ , the mean value for visual acuity. These four numbers designate the extent to which heredity is responsible for visual acuity, the intensity with which selection acts to prize it, the way its mean or average value is spread over a pop-

<sup>2</sup> A graded-index lens is a lens that is not optically homogeneous; the figure of 1.52 is "the value close to the upper limit for biological material."

ulation, and the mean or average value itself. Values are assigned as estimates to the first three numbers; the mean is left undetermined, rising through each generation.

As for the estimates themselves, Nilsson and Pelger assume that  $h^2 = .50$ ; that  $i = 0.01$ ; and that  $V = 0.01$ . On this basis, they conclude that  $R = 0.00005m$ . The response in each new generation of light-sensitive patches is 0.00005 times the mean value of visual acuity in the previous generation of light-sensitive patches.

Their overall estimate—the conclusion of their paper—now follows in two stages. Assume that  $n$  represents the number of generations required to transform a light-sensitive patch into a “focused camera-type eye with the geometry typical for aquatic animals.” (In small aquatic animals, a generation is roughly a year.) If, as we have seen, the mean value of visual acuity of such an eye is  $1.01^{1,829} = 80,129,540$ , where 1,829 represents the number of steps required and 80,129,540 describes the extent of the change those steps bring about; and if  $1.00005^n = 1.01^{1,829} = 80,129,540$ , then it follows that  $n = 363,992$ .

It is this figure—363,992—that allows Nilsson and Pelger to conclude at last that “the time required [is] amazingly short: only a few hundred thousand years.” And this also completes my exposition of Nilsson and Pelger’s paper. Business before pleasure.

**N**ILSSON AND Pelger’s work is a critic’s smorgasbord. Questions are free and there are second helpings.

Every scientific paper must begin somewhere. Nilsson and Pelger begin with their assumption that, with respect to the eye, morphological change comes about by invagination, aperture constriction, and lens formation. Specialists may wish to know where those light-sensitive cells came from and why there are no other biological structures coordinated with or contained within the interior of the initial patch—for example, blood vessels, nerves, or bones. But these issues may be sensibly deferred.

Not so the issues that remain. Nilsson and Pelger treat a biological organ as a physical system, one that is subject to the laws of theoretical optics. There is nothing amiss in that. But while theoretical optics justifies a *qualitative* relationship between visual acuity on the one hand and invagination, aperture constriction, and lens formation on the other, the relationships that Nilsson and Pelger specify are tightly *quantitative*. Numbers make an appearance in each of their graphs: the result, it is

claimed, of certain elaborate calculations. But no details are given either in their paper or in its bibliography. The calculations to which they allude remain out of sight, if not out of mind.

The 1-percent steps: in what units are they expressed? And how much biological change is represented by each step? Nilsson and Pelger do not say. Nor do they coordinate morphological change, which they treat as simple, with biochemical change, which in the case of light sensitivity is known to be monstrously complex.

Does invagination represent a process in which the patch changes as a whole, like a balloon being dimpled, or is it the result of various local processes going off independently as light-sensitive cells jostle with one another and change their position? Are the original light-sensitive cells the complete package, or are new light-sensitive cells added to the ensemble as time proceeds? Do some cells lose their sensitivity and get out of the light-sensing business altogether? We do not know, because Nilsson and Pelger do not say.

Biologists commenting on Darwin’s theory have almost always assumed that evolution reflects what the French biologist François Jacob called *bricolage*—a process of tinkering. Biological structures are put together out of pieces; they adapt their function to changes in their circumstances; they get by. This suggests that in the case of eye formation, morphological change might well purchase less visual acuity than Nilsson and Pelger assume, the eye being tinkered into existence instead of flogged up an adaptive peak. But if, say, only half as much visual acuity is purchased for each of Nilsson and Pelger’s 1-percent steps, twice as many steps will be needed to achieve the effect they claim. What is their justification for the remarkably strong assertion that morphological transformations purchase an optimal amount of visual acuity at each step?

Again we do not know, because they do not say.

More questions—and we have not even finished the hors d’oeuvres. The plausibility of Nilsson and Pelger’s paper rests on a single number: 1,829. But without knowing precisely how the number 1,829 has been derived, the reader has no way of determining whether it is reasonable or even meaningful.

If nothing else, the number 1,829 represents the maximum point of a curve juxtaposing visual acuity against morphological transformation. Now, a respect for the ordinary mathematical decencies would suggest that the curve is derived from the number, and the number from various calculations. But all such calculations are missing from Nilsson and Pelger’s paper. And if the calculations are not

given, neither are any data. Have Nilsson and Pelger, for example, *verified* their estimate, either by showing that 1,829 1-percent steps do suffice to transform a patch into an eye, or by showing that such an eye may, in 1,829 1-percent steps, be resolved backward into an initial light-sensitive patch? Once again, we do not know because they do not say.

Still other questions suggest themselves. Although natural selection is mentioned by Nilsson and Pelger, it is a force that plays no role in their reasoning. Beyond saying that it "constantly favors an increase in the amount of detectable spatial information," they say nothing at all. This is an ignominious omission in a paper defending Darwinian principles. An improvement in visual acuity is no doubt a fine thing for an organism; but no form of biological change is without cost.

Let us agree that in the development of an eye, an initial light-sensitive patch in a given organism becomes invaginated over time. Such a change requires a corresponding structural change to the organism's anatomy. If nothing else, the development of an eye requires the formation of an eye socket—hardly a minor matter in biological terms. Is it really the case that an organism otherwise adapted to its environment would discover that the costs involved in the reconstruction of its skull are nicely balanced by what would initially be a very modest improvement in sensitivity to light? I can imagine the argument going either way, but surely an argument is needed.

Then there is Nilsson and Pelger's data-free way with statistics. What is the basis of the mathematical values chosen for the numbers they use in assessing how rapidly transformation spreads in a population of eye patches? The coefficient of variation is the ratio of the standard deviation to the mean. The standard deviation, one might ask, of *what*? No population figures are given; there are no quantitative estimates of any relevant numerical parameter. Why is selection pressure held constant over the course of 300,000 years or so, when plainly the advantages to an organism of increasing light sensitivity will change at every step up the adaptive slope? Why do they call their estimates pessimistic (that is, conservative) rather than wildly optimistic?

Finally, Nilsson and Pelger offer an estimate of the number of *steps*, computed in 1-percent (actually, 1.00005-percent) intervals, that are required to transform their initial patch. At one point, they convert the steps into generations. But a step is not a temporal unit, and, for all anyone knows, each

step could well require half again or twice the number of generations they suggest. Why do Nilsson and Pelger match steps to generations in the way they do? I have no idea, and they do not say.

**W**E ARE at last at the main course. Curiously enough, it is the intellectual demands imposed by Darwin's theory of evolution that serve to empty Nilsson and Pelger's claims of their remaining plausibility.

Nilsson and Pelger assert that only 363,992 generations are required to generate an eye from an initial light-sensitive patch. As I have already observed, the number 363,992 is derived from the number 80,129,540, which is derived from the number 1,829—which in turn is derived from nothing at all. Never mind. Let us accept 1,829 *pour le sport*. If Nilsson and Pelger intend their model to be a vindication of Darwin's theory, then changes from one step to another must be governed by random changes in the model's geometry, followed by some mechanism standing in for natural selection. These are, after all, the crucial features of *any* Darwinian theory. But in their paper there is no mention *whatsoever* of randomly occurring changes, and natural selection plays only a ceremonial role in their deliberations.

At the beginning of their paper, Nilsson and Pelger write of their initial light-sensitive patch that "we expose this structure to selection pressure favoring spatial resolution" (emphasis added), and later that "[a]s the lens approaches focused conditions, *selection pressure* gradually appears to . . . adjust its size to agree with Mattiesen's ratio" (emphasis added). But whatever Nilsson and Pelger may have been doing to their patch, they have not been exposing it to "selection pressure." The patch does only what they have told it to do. By the same token, selection pressures play no role in adjusting the size of their lenses to agree with Mattiesen's ratio. That agreement is guaranteed, since it is Nilsson and Pelger who bring it about, drawing the curve and establishing the relevant results. What Nilsson and Pelger *assume* is that natural selection would track their results; but this assumption is never defended in their paper, nor does it play the slightest role in their theory.

And for an obvious reason: if there are no random variations occurring in their initial light-sensitive patch, then natural selection has nothing to do. And there are no random variations in that patch, their model succeeding as a defense of Darwin's theory only by first emptying the theory of its content.

An example may make clearer both the point

and its importance. Only two steps are required to change the English word "at" to the English word "do": "at" to "ao" and "ao" to "do." The changes are obvious: they have been *designed* to achieve the specified effect. But such design is forbidden in Darwinian theory. So let us say instead, as Darwin must, that letters are chosen randomly, for instance by being fished from an urn. In that case, it will take, on average, 676 changes (26 letters times 26) to bring about the same two steps.

Similarly, depending on assessments of probability, the number of changes required to bring about a single step in Nilsson and Pelger's theory may range widely. It may, in fact, be anything at all. How long would it take to transform a light-sensitive patch into a fully functioning eye? It all depends. It all depends on how *likely* each morphological change happens to be. If cells in their initial light-sensitive patch must discover their appointed role by chance, all estimates of the time required to bring about just the transformations their theory demands—invagination, aperture construction, and lens formation—will increase by orders of magnitude.

If Darwin were restored to pride of place in Nilsson and Pelger's work, the brief moment involved in their story would stretch on and on and on.

**F**INALLY, THERE is the matter of Nilsson and Pelger's computer simulation, in many ways the gravamen of my complaints and the dessert of this discussion.

A computer simulation of an evolutionary process is not a mysterious matter. A theory is given, most often in ordinary mathematical language. The theory's elements are then mapped to elements that a computer can recognize, and its dynamical laws, or laws of change, are replicated at a distance by a program. When the computer has run the program, it has simulated the theory.

Although easy to grasp as a concept, a computer simulation must meet certain nontrivial requirements. The computer is a harsh taskmaster, and programming demands a degree of specificity not ordinarily required of a mathematical theory. The great virtue of a computer simulation is that if the set of objects is large, and the probability distribution and fitness function complicated, the computer is capable of illustrating the implications of the theory in a way that would be impossible using ordinary methods of calculation. "Hand calculations may be sufficient for very simple models," as Robert E. Keen and James Spain write in their standard text, *Computer Simulation in Biology* (1992), "but computer simulation is almost essential for

understanding multi-component models and their complex interrelationships."

Whatever the merits of computer simulation, however, they are beside the point in assessing Nilsson and Pelger's work. In its six pages, their paper contains no mention of the words "computer" or "simulation." There are no footnotes indicating that a computer simulation of their work exists, and their bibliography makes no reference to any work containing such a simulation.

Curious about this point, I wrote to Dan-Erik Nilsson in the late summer of 2001. "Dear David," he wrote back courteously and at once,

You are right that my article with Pelger is not based on computer simulation of eye evolution. I do not know of anyone else who [has] successfully tried to make such a simulation either. But we are currently working on it. To make it behave like real evolution is not a simple task. At present our model does produce eyes gradually on the screen, but it does not look pretty, and the genetic algorithms need a fair amount of work before the model will be useful. But we are working on it, and it looks both promising and exciting.

These are explicit words, and they are the words of the paper's senior author. I urge readers to keep them in mind as we return to the luckless physicist Matt Young. In my COMMENTARY essay of last December, I quoted these remarks by Mr. Young:

Creationists used to argue that . . . there was not enough time for an eye to develop. A computer simulation by Dan-Erik Nilsson and Susanne Pelger gave the lie to that claim.

These, too, are forthright words, but as I have just shown, they are false: Nilsson and Pelger's paper contains no computer simulation, and no computer simulation has been forthcoming from them in all the years since its initial publication. Sheer carelessness, perhaps? But now, in responding to my COMMENTARY article, Matt Young has redoubled his misreading and proportionately augmented his indignation. The full text of his remarks appears in last month's COMMENTARY; here are the relevant passages:

In describing the paper by Nilsson and Pelger . . . , I wrote that they had performed a computer simulation of the development of the eye. I did not write, as Mr. Berlinski suggests, that they used nothing more than random variation and natural selection, and I know of no reference that says they did.

. . . The paper by Nilsson and Pelger is a sophisticated simulation that even includes quantum noise; it is not, contrary to Mr. Berlinski's assertion, a back-of-the-envelope calculation. It begins with a flat, light-sensitive patch, which they allow to become concave in increments of 1 percent, calculating the visual acuity along the way. When some other mechanism will improve acuity faster, they allow, at various stages, the formation of a graded-index lens and an iris, and then optimize the focus. Unless Nilsson and Pelger performed the calculations in closed form or by hand, theirs was, as I wrote, a "computer simulation." Computer-*aided* simulation might have been a slightly better description, but not enough to justify Mr. Berlinski's sarcasm at my expense. . . .

And here is my familiar refrain: there is *no* simulation, "sophisticated" or otherwise, in Nilsson and Pelger's paper, and their work rests on no such simulation; on this point, Nilsson and I are in complete agreement. Moreover, Nilsson and Pelger do *not* calculate the visual acuity of any structure, and certainly not over the full 1,829 steps of their sequence. They suggest that various calculations have been made, but they do not show how they were made or tell us where they might be found. At the very best, they have made such calculations for a handful of data points, and then joined those points by a continuous curve.

There are two equations in Nilsson and Pelger's paper, and neither requires a computer for its solution; and *there are no others*. Using procedures very much like Nilsson and Pelger's own, Mr. Young has nevertheless deduced the existence of a missing computer simulation on theoretical grounds: "Unless Nilsson and Pelger performed the calculations in closed form or by hand, theirs was, as I wrote, a computer simulation." But another possibility at once suggests itself: that Nilsson and Pelger did not require a computer simulation to undertake their calculations because they made no such calculations, their figure of 1,829 steps representing an overall guess based on the known optical characteristics of existing aquatic eyes.

Whatever the truth—and I do not know it—Mr. Young's inference is pointless. One judges a paper by what it contains and one trusts an author by what he says. No doubt Matt Young is correct to observe that "computer-*aided* simulation might have been a better description" of Nilsson and Pelger's work. I suppose one could say that had Dan-Erik Nilsson and Susanne Pelger rested their heads

on a computer console while trying to guess at the number of steps involved in transforming a light-sensitive patch into a fully functioning eyeball, their work could also be represented as computer-aided.

MATT YOUNG is hardly alone in his lavish misreadings. The mathematician Ian Stewart, who should certainly know better, has made virtually the same patently false claims in *Nature's Numbers* (1995). So have many other prominent figures.<sup>3</sup> But misreadings are one thing, misrepresentations another. More than anyone else, it has been Richard Dawkins who has been responsible for actively misrepresenting Nilsson and Pelger's work, and for disseminating worldwide the notion that it offers a triumphant vindication of Darwinian principles.

In a chapter of his 1995 book, *River Out of Eden*, Dawkins writes warmly and at length about Nilsson and Pelger's research.<sup>4</sup> Here is what he says (emphasis added throughout):

[Their] task was to set up *computer models* of evolving eyes to answer two questions . . . [.] is there a smooth gradient of change, from flat skin to full camera eye, such that every intermediate is an improvement? . . . [and] how long would the necessary quantity of evolutionary change take?

In their *computer models*, Nilsson and Pelger made no attempt to simulate the internal workings of cells.

. . . Nilsson and Pelger began with a flat retina atop a flat pigment layer and surmounted by a flat, protective transparent layer. The transparent layer was allowed to undergo localized random mutations of its refractive index. They then let the model transform itself at random, constrained only by the requirement that any change must be small and must be an improvement on what went before.

The results were swift and decisive. A trajectory of steadily mounting acuity led unhesitatingly from the flat beginning through a shallow indentation to a steadily deepening cup, as the shape of the model eye deformed itself on the computer screen. . . . And then, almost like a conjuring trick, a portion of this transparent filling

<sup>3</sup> Among those who, by contrast, have raised (on the Internet) points similar to my own, I would single out especially Brian Harper, a professor of mechanical engineering at Ohio State University.

<sup>4</sup> A version of the same material by Dawkins, "Where D'you Get Those Peepers," was published in the *New Statesman* (July 16, 1995).

condensed into a local, spherical region of higher refractive index.

. . . This ratio is called Mattiessen's ratio. Nilsson and Pelger's *computer-simulation model homed in* unerringly on Mattiessen's ratio.

How very remarkable all this is—inasmuch as there are no computer models mentioned, cited, or contained in Nilsson and Pelger's paper; inasmuch as Dan-Erik Nilsson denies having based his work on any computer simulations; inasmuch as Nilsson and Pelger never state that their task was to "set up computer models of evolving eyes" for any reason whatsoever; inasmuch as Nilsson and Pelger assume but do not prove the existence of "a smooth gradient of change, from flat skin to full camera eye, such that every intermediate is an improvement"; and inasmuch as the original light-sensitive patch in Nilsson and Pelger's paper was never allowed to undergo "localized random mutations of its refractive index."

And how very remarkable again—inasmuch as there are no computer "screens" mentioned or cited by Nilsson and Pelger, no indication that their illustrations were computer-generated, and no evidence that they ever provided anyone with a real-time simulation of their paper where one could observe, "almost like a conjuring trick," the "swift and decisive" results of a process that they also happen to have designed.

And yet again how very remarkable—inasmuch as Nilsson and Pelger's "computer-simulation model" did not home in unerringly on Mattiessen's ratio, Nilsson and Pelger having done all the homing themselves and thus sparing their model the trouble.

Each and every one of these very remarkable assertions can be explained as the result of carelessness only if one first indicts their author for gross incompetence.

**F**INAL QUESTIONS. Why, in the nine years since their work appeared, have Nilsson and Pelger never dissociated themselves from claims about their work that they know are unfounded? This may not exactly be dishonest, but it hardly elicits admiration. More seriously, what of the various masters of indignation, those who are usually so quick to denounce critics of Darwin's theory as carrying out the devil's work? Eugenie Scott, Barbara Forrest, Lawrence Krauss, Robert T. Pennock, Philip Kitcher, Kelly Smith, Daniel Dennett, Paul Gross, Ken Miller, Steven Pinker—they are all warm from combat. Why have they never found reason to bring up the matter of the mammalian eye and the computer simulation that does not exist?

And what should we call such a state of affairs? I suggest that scientific fraud will do as well as any other term.

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## CONTROVERSY

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# A Scientific Scandal?

## *David Berlinski & Critics*

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DAN-E. NILSSON:

I appreciate the opportunity to respond to David Berlinski's essay on the 1994 paper I authored with Susanne Pelger called "A Pessimistic Estimate of the Time Required for an Eye to Evolve" ["A Scientific Scandal," April]. Because it gives them credibility, I generally do not debate pseudo-scientists, but I have decided to make an exception here.

Apart from a mix-up in chronology and some other minor peculiarities, the only major flaw in Mr. Berlinski's description of our paper is his misunderstanding of the response variable R, which he calls a measure of "visual acuity." It is not, and the original paper does not say so. This is his first serious mistake—and it gets worse.

Mr. Berlinski's next move is to list the important information he claims is missing in our paper. (At regular intervals he repeats the phrase: "they do not say.") But all the necessary information is there. I cannot reply individually to every point here, but two examples will do. Mr. Berlinski claims that there is no unit for morphological change and that

we do not explain how we arrive at a sum of 1,829 steps of 1 percent, but explanations for both are given on page 56 of our paper. He further claims that we fail to explain how morphological change relates to improvements in visual acuity, though pages 54 through 56 (together with the graphs and legends in figures 1 and 3) deal with exactly that, and in great detail.

For the rest of his essay Mr. Berlinski focuses on issues where he believes he has detected logical flaws. He is not right in a single case, and instead reveals an insufficient background in visual optics, sampling theory, basic evolutionary theory, and more. Nor does he seem to have read key references such as Warrant & McIntyre (1993), Falconer (1989), or Futuyma (1986). Without such knowledge it would be hard to grasp the details of our paper, but it is standard scientific practice not to repeat lengthy reasoning when a short reference can be given.

But there is more. Mr. Berlinski has a problem with definitions. "Morphological change" becomes "biological change." "Spatial reso-

lution" (visual acuity) becomes "sensitivity of vision." He does not distinguish between selection and intensity of selection. He is obviously confused by the difference between the 1-percent steps that we use as a unit of measure for morphological change and the 0.005-percent change per generation that is our conservative estimate of evolutionary rate.

Mr. Berlinski attempts a peculiar probability argument involving the random substitution into the word "at" of letters "fished from an urn," but he does not realize that his example implies a single individual in the population, in which case there can of course be no selection at all. Again, he badly needs to read Falconer's standard work.

Contrary to Mr. Berlinski's claim, we calculate the spatial resolution (visual acuity) for all parts of our eye-evolution sequence, and the results are displayed in figure 1 of our paper. The underlying theory is explained in the main text, including the important equation 1 and a reference to Warrant & McIntyre (1993), where this theory is derived. Yet Mr. Berlinski insists that "Nils-

son and Pelger do *not* calculate the visual acuity of any structure." It would be much simpler for Mr. Berlinski if he went just a tiny step farther and denied the existence of our paper altogether.

Had these and other points been unfortunate misunderstandings, I would have been only too happy to help, but I have the distinct impression that they are deliberate attempts to eliminate uncomfortable scientific results. Why does Mr. Berlinski not read up on the necessary scientific background? Why does he so blatantly misquote our paper? Why has he never asked me for the details of the calculation he claims to want so badly? It is simply impossible to take Mr. Berlinski seriously.

Mr. Berlinski is right on one point only: the paper I wrote with Pelger has been incorrectly cited as containing a computer simulation of eye evolution. I have not considered this to be a very serious problem, because a simulation would be a mere automation of the logic in our paper. A complete simulation is thus of moderate scientific interest, although it would be useful from an educational point of view.

Our paper remains scientifically sound, and has not been challenged in any peer-reviewed scientific journal. I do not intend to take any further part in a meaningless debate with David Berlinski.

*Lund University  
Lund, Sweden*

#### PAUL R. GROSS:

"A Scientific Scandal" is itself a scientific scandal: the continued publication, in a political-cultural opinion journal, of David Berlinski's uninformed bellyaching about evolutionary biology. COMMENTARY is not the place for quasi-technical arguments against Darwinism, or for reprinting the scientific papers or textbook chapters that disprove them.

Mr. Berlinski has several times found fault with me. The method is characteristic, and it is salient in this

latest article. I had written earlier that his disparagements of Darwinism are old and naive, refuted in the literature. Responding in the March issue ("Darwinism versus Intelligent Design"), he dismissed this airily as an unanswerable gripe. But it is not a gripe. Nor was it meant to be answered in COMMENTARY. It is just a fact about the scientific literature. Any reader can check for himself. Examples include: Mark Ridley, *Evolution*, 2nd Edition (1996); John Gerhart and Marc Kirschner, *Cells, Embryos, and Evolution* (1997); Rudolf A. Raff, *The Shape of Life* (1996).

Only once, in the eleven years since the start of their anti-evolution PR-blitz, have any arguments of Mr. Berlinski's colleagues at the Discovery Institute's Center for Science and Culture appeared in the primary literature. That was an early philosophical monograph by the Christian apologist William Dembski. Mr. Berlinski (in "Has Darwin Met His Match?", December 2002) now rejects that argument as applied to biology, although he gave Dembski's book a glowing blurb. The rest of their anti-evolution kvetching has been in trade books mainly from religious publishers, in nonscientific journals, testimony to legislators, interviews, speeches, and rallies for the faithful. For this, Mr. Berlinski offered the crank excuse: scientific prejudice. And as *coup de main*, he quoted lines from a 1986 essay of mine. But the burden of that essay is precisely the opposite of Mr. Berlinski's reason for quoting it. It was about a distinguished regular contributor to the scientific literature.

The obvious purpose of "A Scientific Scandal," like Mr. Berlinski's other adventures in evolutionary thought, is to belittle Darwinism. He cites Darwin himself, who worried a little that his theory might not be able to account for the eye. Mr. Berlinski's real case is that Darwin's fears were justified: evolutionary theory cannot explain the eye, and there has been a cover-up.

But Darwin's fears are ancient history: Darwin was still haunted by Paley's 1802 version of the argument from design. A century and a half have passed.

In the 21st century there is no question that eyes, endlessly varied in structure and quality, have evolved. Most of the intermediates between a primitive patch of photosensitive cells and the camera eye of a fish or a mammal exist. Many more have existed in the past, during the 540 million years since there have been eyes.

So what is the fuss about? In their 1994 theoretical paper, Nilsson and Pelger modeled one possible evolutionary pathway to the geometry of a fish-like eye from a patch of photoreceptive cells. There were already such cells on Earth a billion years before there were eyes. Nilsson and Pelger used pessimistic estimates of such relevant parameters as the intensity of selection for their number-crunching. The point was to determine how many plausible, populational micro-steps of variation would be needed for very weak selection to yield a fish-like eye—and then under reasonable assumptions to convert micro-steps into generations and years. The answer was about 350,000—a geological blink of the eye. This answer is just one of many to the failed 19th-century complaint of insufficient time for evolution to have taken place.

Mr. Berlinski misunderstands or misinterprets critical elements of the paper. Then he quibbles ponderously about terms and assumptions—and about a popular gloss of the paper by Richard Dawkins. He accuses some of his critics of fraud for having failed to denounce Dawkins's use in a trade book of certain of those terms. Mr. Berlinski's arguments are quibbles.

But these quibbles are beside the real point, which is that we lack grounds for believing that eyes evolved. That is false. Eyes, like anything else, could have been invented at a stroke by a supernatural

designer. But there is no evidence of it. Neither can it ever be disproved. The only *explanation*, however, that we have for the structure of eyes—as solid as any explanation in science—is Darwinian evolution.

Like the intelligent-design group as a whole, Mr. Berlinski seems unable or unwilling to understand the newest branch of biology: evolutionary *developmental* biology. There, with the discovery of the developmental regulatory genes, we have learned how subtle, how versatile, and yet how simple the mechanisms can be for transforming one biological structure to another. (A professional but accessible account can be found in *From DNA to Diversity: Molecular Genetics and the Evolution of Animal Design* [2001] by Sean B. Carroll, Jennifer K. Grenier, and Scott D. Weatherbee. A popular but sound insight is available in: "Which Came First, the Feather or the Bird?" by Richard O. Prum and Alan H. Brush, *Scientific American*, March 2003.) A reader whose view of science comes only from Mr. Berlinski will never know of such things.

*Jamaica Plain, Massachusetts*

#### MATT YOUNG:

Creationists often claim, without presenting evidence, that there has not been enough time for a complex organ such as the eye to have evolved. To examine that claim empirically, Nilsson and Pelger devised a scenario in which an eye could have evolved through stages that are known to exist in the animal kingdom. I described their scenario in my last letter to COMMENTARY (March), and David Berlinski has it almost right in "A Scientific Scandal."

Briefly, Nilsson and Pelger formed an eye by changing various parameters, such as aperture diameter, in 1-percent increments, until no improvement could be made. One percent is an arbitrary number (any small increment will suffice) and does not represent the change in a single generation. Using what they and Richard Dawkins describe as conservative

numbers, Nilsson and Pelger calculated an average change of 0.005 percent per generation. The relative change in  $n$  generations is therefore  $(1.00005)^n$ , which they set equal to the overall change of morphology in their simulation ( $1.01^{1,829}$ , where 1,829 is the number of 1-percent steps required to form an eye). The number 1.00005 is not, contrary to Mr. Berlinski, a percentage; it is the relative change of a given parameter in a single generation. Nilsson and Pelger concluded that an eye could have evolved in approximately 350,000 years.

Does anyone claim that an eye evolved precisely as Nilsson and Pelger's simulation suggests? No. But I stand by my statement that they have given the lie to the creationists' claim and firmly made the case that an eye could have evolved within a geologically short time.

Mr. Berlinski argues, for example, that morphological changes of the skull might slow the process. Never mind that only vertebrates have skulls, and Nilsson and Pelger's eye is, again contrary to Mr. Berlinski, an invertebrate eye. The development of an eye will require not only morphological changes but also advancements to the nervous system and the brain. Will these requirements bring evolution to a halt? Georges Cuvier asked the same question in 1812, and the answer is, "no." We now know that evolution progresses in a modular way, with different systems evolving in parallel and nearly independently. If Mr. Berlinski thinks that various modules could not have co-evolved, he needs to support his argument quantitatively, not just proclaim it. Nilsson and Pelger have shown precisely what they set out to show: that an eye could have evolved in a geologically short time and that the eye itself is not a limiting factor. Mr. Berlinski holds against them that they did not perform the full-fledged simulation he wants them to have done and seems to think that their calculation is therefore somehow faulty.

I will not respond to Mr. Berlinski's disdainful tone, nor to the cheap shots directed at me personally. Nor will I continue the pointless distraction of whether Nilsson and Pelger performed a simulation or a calculation. I am, however, concerned with Mr. Berlinski's contention that reputable scientists have conspired to support a technical paper that he finds "unfounded"; charging specific individuals with "fraud" is not to be taken lightly. The paper has survived peer review, and has not been shown to be unfounded in any peer-reviewed journal. If Mr. Berlinski thinks the paper is unfounded, let him submit a paper of his own to a peer-reviewed journal and find out what the scientific community thinks of his ideas. It is unlikely that scientific journals, which have occasionally published papers on homeopathic medicine and the Bible codes, would reject Mr. Berlinski's paper out of sheer prejudice.

*Colorado School of Mines  
Golden, Colorado*

#### MARK PERAKH:

It is funny that COMMENTARY—by no measure a scientific publication—has allocated so much space to recent articles by David Berlinski. With no record of scientific research, either in biology or in computer science, he sets out to pronounce judgment on topics within these two fields.

But contrary to Mr. Berlinski's rhetoric, any scandal related to Nilsson and Pelger's paper occurred only in Mr. Berlinski's imagination. Nilsson and Pelger estimate the time necessary for the development of an eye, a calculation that entails certain assumptions but which is viewed by many scientists as sufficiently sound. (According to the *Science Citation Index*, Nilsson and Pelger's article has been positively referenced in at least 25 peer-reviewed scientific publications.)

But Mr. Berlinski, unlike all these scientists, does not like Nilsson and

Pelger's conclusion, and obfuscates the issue by discussing the distinctions among computer simulations, models, and calculations. These semantic exercises are inconsequential to the real question: whether an eye could have developed in a geologically short time via a Darwinian mechanism, as Nilsson and Pelger and scores of biologists familiar with their work think.

A reader cannot fail to notice an especially appalling feature of Mr. Berlinski's escapade: he accuses ten respected scientists of "scientific fraud." The reason for that preposterous accusation is that they did not repudiate Nilsson and Pelger's work. Mr. Berlinski apparently cannot imagine that these scientists, among them professional biologists and physicists with records of substantial achievement, can have an opinion of Nilsson and Pelger's work different from his own. His accusation sounds even odder coming from a man who provided rave blurbs for books by William Dembski and Michael Behe even though, as is clear from his article in the December 2002 *COMMENTARY*, he is actually in disagreement with them regarding essential parts of their assertions. Maybe by his standards this is a manifestation of integrity, but to me it looks more like an expediency whose roots are not exactly in the search for scientific truth.

*Bonsall, California*

#### JASON ROSENHOUSE:

Connoisseurs of pseudoscience will recognize in David Berlinski's latest essay the standard tropes of the crank's playbook: the smug sarcastic tone, the barrage of bullet-point criticisms to create the illusion that something truly rotten is being exposed (criticisms he knows will be answered by nothing more formidable than a few indignant letters), the crude baiting of scholars of vastly greater accomplishment than he, and the presentation of minor errors as tantamount to fraud.

Mr. Berlinski has no interest in

bringing clarity to difficult scientific issues. If he did, he would not have made so many misrepresentations in describing Nilsson and Pelger's work. Two examples: Mr. Berlinski's claim that their model eyes were simply "flogged up an adaptive peak" ignores the fact that establishing the existence of such a peak was one of the primary accomplishments of the paper. That there is a smooth gradient of increasing visual acuity linking a light-sensitive spot to a lens-bearing eye is a discovery that they made, not a foregone conclusion. And his claim that "in their paper there is no mention whatsoever of randomly occurring changes" falls flat, since the need for such changes is explicitly mentioned in the discussion section of the paper, and is plainly implied throughout.

In addition, Mr. Berlinski would not have unloaded so many spurious criticisms. For example, his query—"why is selection pressure held constant over the course of 300,000 years"—is easily answered by noting that it was held constant at a value that was ludicrously low for almost any environment.

Once we have swept the field of Mr. Berlinski's distortions we are left with a few simple facts. (1) Several decades of research on the evolution of eyes has not only made it plain that eyes have evolved, but has also revealed the major steps through which they did so. (2) Nilsson and Pelger's paper provides an elegant capstone for this research, by providing a convincing calculation for an upper limit on the time required for an eye to evolve. (3) Minor errors in popular treatments of Nilsson and Pelger's paper do nothing to change facts (1) and (2). (4) Finally, David Berlinski is not a reliable source for scientific information.

*Kansas State University  
Manhattan, Kansas*

#### NICK MATZKE:

David Berlinski should be congratulated for pointing out Richard Dawkins's inaccurate description of

Nilsson and Pelger's paper as a stochastic computer simulation of the evolution of the eye (it was actually a mathematical model). But Mr. Berlinski should remove the plank from his own (discussion of the) eye. He asserts that one of the problems that Nilsson and Pelger did not consider was how the skull would be "reconstructed" to include eye sockets. But as any decent student of even high-school biology would know, eyes evolved before bones. Cephalochordates, the closest invertebrate relatives of vertebrates, have primitive eyes but no bones. In fact, based on genetic evidence, many biologists now think that vertebrate eyes share a common ancestral eyespot with insect eyes.

To envision the evolution of the eye as occurring on some kind of mythical eyeless fish with a fully formed skull and brain is a typical creationist straw man. Biologists know that all manner of gradations of eye complexity exist in extant organisms, from creatures with a single photoreceptor cell, through the various stages that Nilsson and Pelger depict, to the advanced camera-eyes of mammals and cephalopods. Sometimes the whole sequence from eyespot to advanced eye with lens can be seen in a single group (e.g., snails), yet another thing Mr. Berlinski would have known had he followed Nilsson and Pelger's reference to the classic work on eye evolution, a 56-page article by Salvini-Plawen and Mayr in *Evolutionary Biology* (vol. 10, 1977) called "On the Evolution of Photoreceptors and Eyes." That paper answers many of the questions that Mr. Berlinski asserts are unanswered or unanswerable.

If Mr. Berlinski is going to declare as bunk the central organizing theory of biology, he should take the matter up with biologists in the professional literature rather than in forums like *COMMENTARY*, wherein elementary questions like "which came first, skulls or eyes?" can be botched and yet still be published.

*Goleta, California*

**DAVID SAFIR:**

Once again, David Berlinski has shown how a truly scientific inquiry can expose academic and intellectual fraud by evolutionists. As a physician, I have always been made uneasy by the assertions offered by proponents of evolution to explain complex biological life. Mr. Berlinski shows exactly how the process works: start with the belief that no other possible explanation for the diversity of life on earth could exist other than what we think we know about evolution; demonstrate utter contempt for other ideas (ad-hominem attacks are often employed here); then simply invent a pathway describing how it might have been possible to get from point A to point B—from a light-sensitive spot, say, to a complex eye. Where I come from this is called nonsense.

I would feel better about a theorist like Richard Dawkins if he did not pontificate about how gloriously perfect his explanations are. I cast my fate instead with scientists like Mr. Berlinski who keep an open mind. The jury is still out, after all, and will be for a very long time.

*Los Gatos, California*

**NORMAN P. GENTIEU:**

As a retired science writer, I appreciated David Berlinski's superb analysis refuting Nilsson and Pelger's simplistic scenario of the evolution of the mammalian eye. To account for the perfection of that incredibly complex organ by means of formulaic fumblings is nothing less than preposterous. I wonder if Nilsson and Pelger might some day use this iffy method to explain the development of stereoscopic color vision.

"A Scientific Scandal" is an apt name for the docile acceptance of a dubious theory. What has happened to vetting? Back in the 1950's, the science establishment did not hesitate to zap Immanuel Velikovsky and his *Worlds in Collision*.

*Philadelphia, Pennsylvania*

**David Berlinski**

In "A Scientific Scandal," I observed that Dan-E. Nilsson and Susanne Pelger's paper, "A Pessimistic Estimate of the Time Required for an Eye to Evolve," was a critic's smorgasbord. There are so many things wrong with it that even the finickiest of eaters could leave the table well-satisfied and ready for a round of Alka-Seltzer. But, in itself, there is nothing here that suggests a scandal. Dan-E. Nilsson is a distinguished scientist. Witness his discovery that the mysid shrimp, *Diaptomysis pauciponisa*, is an organism whose eyes are at once simple and compound (D. Nilsson, R.F. Modlin, "A Mysid Shrimp Carrying a Pair of Binoculars," *Journal of Experimental Biology*, Vol. 189, pp. 213-236, 1994), or his precise work on the optical system of the butterfly (D. Nilsson, M.F. Land, J. Howard, "Optics of the Butterfly Eye," *Journal of Comparative Physiology*, A 162, 341-366, 1988). Together with Susanne Pelger, he has simply written a silly paper. It happens. And in the literature of evolutionary biology, it happens very often.

No, the scientific scandal lies elsewhere. Nilsson and Pelger's paper has gained currency in both the popular and the scientific press because it has been misrepresented as a computer simulation, most notably by Richard Dawkins. Word spread from Dawkins's mouth to any number of eagerly cupped but woefully gullible ears. Subsequent references to Nilsson and Pelger's work have ignored what they actually wrote in favor of that missing computer simulation, in a nice example of a virtual form of virtual reality finally displacing the real thing altogether. This misrepresentation of scientific work is a species of fraud, no different in kind from plagiarism in journalism or the fabrication of data in experimental physics. It is the indifference to this fraud that I denounce as scandalous.

Recognizing so many fond familiar faces among my critics—Paul

Gross, Jason Rosenhouse, Matt Young, and Mark Perakh have replied to previous essays of mine in COMMENTARY—I hoped that self-interest, if nothing else, might have prompted a moment of critical self-reflection. No very delicate moral sense is involved in determining that fraud is fraud. If Richard Dawkins is one of their own, all the more reason to apply to him the moral standards that Messrs. Gross, Rosenhouse, Young, and Perakh are accustomed to applying to their intellectual enemies.

Reading their letters, I realize that they had no intention of saying boo. What could I have been thinking?

DAN-E. NILSSON is persuaded that I wrote my essay because I am moved to reject "uncomfortable scientific results." He is mistaken. The length of time required to form an eye is a matter of perfect indifference to me; had he and Susanne Pelger been able to demonstrate that the eye was in fact formed over the course of a long weekend in the Hamptons, I would have warmly congratulated them. As I have many times remarked, I have no creationist agenda whatsoever and, beyond respecting the injunction to have a good time all the time, no religious principles, either. Evolution long, evolution short—it is all the same to me. I criticized their work not because its conclusions are unwelcome but because they are absurd.

The vertebrate eye, Nilsson and Pelger claim, emerged from a patch of light-sensitive cells. Climbing up evolution's greasy pole, or adaptive peak, those cells got to where they were going by invagination, aperture constriction, and lens formation. In explaining the evolution of the eye in terms of such global geometrical processes, Nilsson and Pelger rather resemble an art historian prepared to explain the emergence of the *Mona Lisa* in terms of preparing the wood, mixing the paint, and filling in the details. The

conclusion—that Leonardo completed his masterpiece in more than a minute and less than a lifetime—while based squarely on the facts, seems rather less than a contribution to understanding.

It is hardly surprising, then, that while theoretical optics serves *qualitatively* to justify the overall connection Nilsson and Pelger draw between morphology and visual acuity, nothing in their paper and nothing in their references justifies the *quantitative* relationships they employ to reach their quantitative conclusion. To be sure, Mr. Nilsson denies that this is so. “Contrary to Mr. Berlinski’s claim,” he writes,

we calculate the spatial resolution (visual acuity) for all parts of our eye-evolution sequence, and the results are displayed in figure 1 of our paper. The underlying theory is explained in the main text, including the important equation 1 and a reference to Warrant & McIntyre (1993), where this theory is derived.

In fact, no underlying theory whatsoever is explained in Nilsson and Pelger’s main text, or in the legend to figure 1; and while they do assert that calculations were made, they do not say where they were made or how they were carried out. The burden of Mr. Nilsson’s denials is conveyed entirely by equation 1 and by his references.

Let us start with equation 1, and with figure 1b that this equation is said to control. It is in figure 1b that aperture constriction takes over from invagination in getting an imaginary eye to see better. The graph juxtaposes aperture size against detectable spatial resolution. Having dimpled itself in figure 1a, Nilsson and Pelger’s blob is now busy puckering its topmost surface to form a pinhole in figure 1b.\* In a general way, the curve they present is unremarkable. No one doubts that spatial resolution is improved in an eye when its aperture is constricted. But why is it im-

proved in just the way that Nilsson and Pelger’s graph indicates?

Equation 1 is of scant help in this regard, despite Nilsson’s insistence that it is important. Drawing a connection among visual acuity, focal length, light intensity, and noise, the equation specifies the local maximum of a curve, the place where it stops rising. In other words, it specifies a point; and it does nothing more. “We can now use this relationship,” Nilsson and Pelger nevertheless declare, “to plot resolution against aperture diameter.” They can do nothing of the sort, at least not in *my* calculus class. Knowing that a man has reached the summit of Mt. Everest, we still know nothing about the route he has taken to get there. What is needed if Nilsson and Pelger are to justify their graph is the equation from which equation 1 has been derived by differentiation. It is not there, just where I said it would not be.

Similarly with Nilsson and Pelger’s references, which do nothing to support their argument. Quite the contrary. Three papers are at issue: (1) A.W. Snyder, S. Laughlin, and D. Stavenga, “Information Capacity of the Eyes” (*Vision Research*, vol. 17, 1163-1175, 1977); (2) A.W. Snyder, “Physics of Vision in Compound Eyes” (in *Vision in Invertebrates*, Handbook of Sensory Physiology, edited by H. Autrum, vol. VII/6A, pp. 225-313, 1979); and (3) E. J. Warrant & P.D. McIntyre, “Arthropod Eye Design and the Physical Limits to Spatial Resolving Power” (*Progress in Neurobiology*, vol. 40, pp. 413-461, 1993). Of these papers, the first is recapitulated (and corrected) in the second, and the second is summarized in the third. In what follows, references to Snyder are always to the Snyder of his second paper.

As their titles might suggest, both “Physics of Vision in Compound Eyes” and “Arthropod Eye Design and the Physical Limits to Spatial Resolving Power” deal with *compound invertebrate* eyes. Nilsson and

Pelger’s work is devoted to the evolution of the *camera* eye characteristic of fish and cephalopods. Theoretical considerations that apply to bugs do not necessarily apply to fish or octopuses, the more so since their eyes are structurally different, as are their evolutionary histories. Writing about the compound eye, Nilsson himself has remarked that “it is only a small exaggeration to say that evolution seems to be fighting a desperate battle to improve a basically disastrous design” (Dan-E. Nilsson, “Optics and Evolution of the Compound Eye,” in *Facets of Vision*, edited by D.G. Stavenga & R.C. Hardie, p. 3075, 1989). Whatever the desperate battle going on among the arthropods, there is no battle at all taking place among the vertebrates or the cephalopods. Nilsson and Pelger’s eye moves from triumph to triumph with serene and remarkable celerity.

If the papers by Snyder and Warrant & McIntyre say nothing about fish or octopuses, neither do they say anything about evolution. No mention there of Darwin’s theory, no discussion of morphology, not a word about invagination, aperture constriction, or lens formation, and *nothing* about the time required to form an eye, whether simple, compound, or camera-like.

The purpose of these three papers is otherwise. No less than any other system of communication, the eye represents a balance struck between signal and noise. There is the object out there in the real world—whether a point source like a star, or an extended source like a grating of light and dark lines—and there is its image trembling on the tips of the retina’s budded nerve cells. Slippage arises between what the object is and how it is seen. Noise occurs in the visual system as the result of the random nature of photon emission, and it also occurs as the result of inherent imperfections in the eye’s op-

\* Three curves are given in figure 1b, representing three different levels of light intensity, but this plays no role in what follows.

tical system. The theoretical optician abbreviates these limitations in one mathematical instrument.

Imagine one of Nilsson and Pelger's plucky light-sensitive cells, and then extend two flanking lines from the cell up past the constricted aperture and out into space, so that the cell and those two flanking lines form a cone with a flat top. In the center of the cone, where a cherry would sit atop the ice cream, there is a light source. The cherry moves to the sides of the cone in angular steps; the cell dutifully responds. The correlation between moving cherry and twitching cell constitutes the optician's "angular-sensitivity function."

Equation B15 (p. 238) in Snyder's "Physics of Vision in Compound Eyes" defines the signal-to-noise ratio of a hypothetical eye in terms of noise, modulation contrast (the difference in intensity between black and white stripes in a grating), and the modulation-transfer function, which is simply a mathematical transformation of the eye's angular-sensitivity function (its Fourier transform). Lumbering in Snyder's footsteps, Warrant & McIntyre split his equation into two of their own (equations 10 and 11 in Warrant & McIntyre, p. 430), the one describing the signal, the other the noise in a hypothetical visual system. They observe what is in any case obvious: whatever the parameters affecting visual acuity, signal and noise will always reach a point where the first is drowned out by the second and the system fails, a point evident enough to anyone trying to see in the dark.

These equations lead by primogeniture to Nilsson and Pelger's equation 1, which, as it happens, does not appear anywhere in their sources in the form in which they express it. But neither Snyder's original equation nor Warrant & McIntyre's bright bursting clones in any way suggest that the tipping point between signal and noise is unique. The ratio of signal to noise in an

optical system depends on a host of factors, including head size and eye movement, most of which Nilsson and Pelger ignore. Nor, for that matter, do these equations taken in isolation justify any particular quantitative conclusions. Until the angular-sensitivity function is specified, whether theoretically or experimentally, its role is ceremonial.

Such specification is no easy busi-

ness. Determining the shape of the angular-sensitivity function is a little like trying to guess an astronaut's weight in space. Scales are not likely to be of use. In an early paper dealing with this subject and devoted experimentally to flies, K.G. Götz noted that the angular-sensitivity function in *Drosophila* seemed to follow what is known mathematically as a Gaussian probability dis-

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tribution (K.G. Götz, "Die optischen Übertragungseigenschaften der Komplexaugen von *Drosophila*," *Kybernetik*, 2, pp. 215-221, 1965). It was an interesting idea, but one that led to very considerable computational difficulties.

Looking Götz-ward, and understandably recoiling, Snyder adopted a different strategy. In assessing the weight of an astronaut in space, it is simpler to count the calories he consumes and the exercise he undergoes than to try to measure his weight directly. His weight, although unmeasured, follows inferentially. In just the same way, Snyder thought to consider the angular-sensitivity function indirectly by considering the structures that determined its shape. These, he assumed, were the eye's retinal receptive field—the area of the retina responding to signals—and its optical "blur spot"—the smeared image represented on the retina corresponding to the sharp object being seen. Let them both, he declared, be identically Gaussian. Why not? Both parameters had simple mathematical natures. The retinal receptive field is given as the ratio of the rhabdom's diameter to its posterior nodal distance, the optical blur as the ratio of the wavelength of stimulating light to the eye's aperture. From this the shape of the angular-sensitivity function followed.

The result is known as the Snyder model. "*The great beauty of this model*," Warrant & McIntyre remark (in words that they have italicized), "*is that if one knows some very simple anatomical information about the eye*"—i.e., the nature of its optical blur spot and retinal receptive field—"one has the ability to predict... the approximate shape of the angular-sensitivity function" (p. 434). In referring to Warrant & McIntyre, Nilsson and Pelger are, in fact, appealing to Snyder, the *maitre* behind their masters—for, like Snyder, they, too, assume that retinal receptive fields and optical blur spots are identically Gaussian (p. 54).

But theory is one thing, and living flesh another. Staking their all on Snyder's model, Nilsson and Pelger must live with its consequences. "Having considered the physical limitations to resolving power," Snyder wrote, "in addition to the absolute sensitivity of eyes, we now apply our concepts to real compound eyes." This is something that Nilsson and Pelger never do. And no wonder. For Snyder then added the rather important caveat that bringing theory to bear on life "requires *precise* knowledge [of various optical parameters] in the various regions of the eye" (Snyder, p. 276, emphasis in the original).

If precise knowledge is needed in applying Snyder's model, precise detail is what is lacking in Nilsson and Pelger's paper. Precise detail? *Any* detail whatsoever.

And for obvious reasons. When tested, Snyder's model turns out to be *false* across a wide range of arthropods. As Warrant & McIntyre note glumly, "The model, on the whole, works best for those eyes for which it was originally formulated—apposition compound eyes functioning according to geometrical optics—but recent careful and sensitive measurements of angular sensitivity reveal that even in these types of eye, the model often performs poorly." Readers may consult figure 34 (p. 441) of Warrant & McIntyre's paper to see how poorly the Snyder model does. In studies of the locust *Locusta*, real and predicted angular-sensitivity functions do not even share the same qualitative shape.

Responding to my observation that no quantitative argument supports their quantitative conclusions—no argument at all, in fact—Mr. Nilsson has thus (1) offered a mathematically incoherent appeal to his only equation; (2) cited references that make no mention of any morphological or evolutionary process; (3) defended a theory intended to describe the evolution of vertebrate camera eyes by referring to

a theory describing the theoretical optics of compound invertebrate eyes; (4) failed to explain why his own work has neglected to specify any relevant biological parameter precisely; and (5) championed his results by means of assumptions that his own sources indicate are false across a wide range of organisms.

In acknowledgments to their paper, Nilsson & Pelger thank E. J. Warrant for help with their computations; in the acknowledgments to *their* paper, Warrant & McIntyre thank Mr. Nilsson for critically reading what they have written.

Schnapps all around, I am sure.

I TURN next to the morphological units that are missing from Nilsson and Pelger's paper. It makes no sense to say of a ruler that it is one long. One what? When the "what" has been specified, a physical unit has been indicated: one inch, say, in the case of length, one pound in the case of weight. If one inch and one pound are units, length and weight are their dimensions. Only an origin in zero remains to be specified to complete the picture.

In my essay, I observed that Nilsson and Pelger had not specified their unit of morphological change. Nilsson now asks me to consider again their remarks on p. 56 of their paper. There, he is certain, I will find the missing unit carefully explained. Here is what they write, and it is *all* that they write: "Our principles have been to use whole-length measurements of straight structures, arc lengths of curved structures, and height and width of voluminous structures."

Very well. These are the fundamental units. They are none too clearly explained—try estimating the volume of a donut by looking at its height and width—but I know roughly what Nilsson and Pelger are getting at. What they do not say is *how* these three separate fundamental units are combined in a single overall derived unit of change.

A homely example may make this

more vivid. Except for the fact that it cannot see, a Swedish meatball is rather like an eye. And plainly it makes no sense to ask of two Swedish meatballs, one of them twice as greasy but half as wide as the other, which of them is bigger—at least not until units of grease and length have been *combined*. But this is, in general, no easy task, not even when shape alone is under consideration. “It is important to keep in mind,” C.P. Klingenberg and L.J. Leamy write (“Quantitative Genetics of Geometric Shape in the Mouse Mandible,” *Evolution*, 55(11), pp. 2342–2352, 2001), “that shape is a multivariate feature and cannot be easily divided into scalar traits without imposing arbitrary constraints on the results of the analysis.” To see how difficult a conceptual problem Nilsson and Pelger have set themselves, readers may follow the trail of Klingenberg & Leamy’s references to the badlands of current work on geometric morphometrics.

Operating perhaps on the principle that a difficulty disclosed is a difficulty denied, Nilsson and Pelger do mention this very point, citing an example of their own on p. 56 to show just how arbitrary can be the business of calculating combined or derived units. In then justifying their own procedure, which is never explained, they remark: “As we are going to relate our measure of morphological change only to general estimates of phenotypic variation” in visual acuity, “we will be safe as long we avoid unorthodox and strange ways of comparing origin and product.”

Origin and product? I am sure they meant origin and unit. No matter. The remark speaks for itself.

THERE IS next the matter of random variation: the heart of the matter so far as I am concerned. Nilsson and Pelger’s paper is not an exercise in theoretical optics. It is intended to serve polemical purposes. Thus, they write: “In this context it is ob-

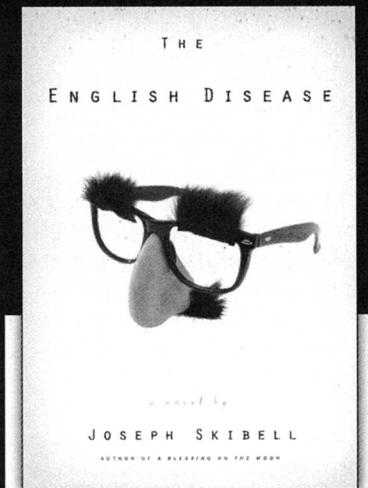
vious that the eye was never a real threat to Darwin’s theory of evolution” (p. 58). By “this context,” they mean one in which only “eye geometry” and “optical structures” are up for grabs. But whether in this context or any other, it is as a defense of Darwin’s theory that Nilsson and Pelger’s theory fails most obviously.

Let me review the chief steps in their argument. There is morphological change on the one hand, visual acuity on the other. As their population of light-sensitive cells alters its geometry—by means never specified—visual acuity perks up. In all, they assert, 1,829 steps are involved in tracing a path from their first patch to their final “product.”

Just how do Nilsson and Pelger’s light-sensitive cells move from one step on that path to the next? I am not asking for the details, but for the odds. There are two possibilities. Having reached the first step on the path, the probability that they will reach the second (and so on to the last) is either one or less than one. If one, their theory cannot be Darwinian—there are no random changes. If less than one, it cannot be right—there is no way to cover 1,829 steps in roughly 300,000 generations if each step must be discounted by the probability of its occurrence.

Demonstrating the existence of a path between two points in the history of life is in general not hard. What is hard is determining how the path was *discovered*. (This was the point of the linguistic example I offered in my essay.) If one assumes, as Nilsson and Pelger do, that probabilities need not be taken into account because all transitions occur with a probability of one, there is no problem to be discussed—but nothing of any conceivable interest, either. In responding to this obvious point by generously suggesting that I need to spend more time by the lamp with D.S. Falconer’s *Principles of Quantitative Genetics*, Mr. Nilsson has covered an embarrassment by addressing an irrelevance. Neither

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population size nor natural selection is at issue.

A few minor matters. Falconer's response variable R is a measure, all right: a measure of the extent to which the mean of some quantitative phenotypic character—snout length, crop yield, scab color, or scrotum size (examples from the literature, I am afraid)—rises or falls as the result of natural selection. Just what I said, just as I explained. Although I offered no definitions in my essay, the paraphrases I employed were harmless. Why not say "sensitivity to vision" instead of "visual acuity," just to vary pace and prose? But in one respect, Mr. Nilsson is right: I did not distinguish between selection and intensity of selection. Neither does he. Neither does Falconer's response statistic, which contains only one selectional parameter, and that one measuring the intensity of selection. Neither does anyone else in this context.

His paper with Susanne Pelger, Mr. Nilsson writes, has never been criticized in the peer-reviewed literature. I am certain that this is so.

**PAUL R. GROSS** takes the occasion of his current letter to assure readers that what he meant in his last letter he did not say and what he said he did not mean. Like golf, Mr. Gross suggested in the 1986 essay from which I uncharitably quoted in the March COMMENTARY, science is rather a clubby affair, and just as a great many men prefer to cover the links sedately in the company of men like themselves—tassels on their shoes, alligators on their polo shirts—so scientists prefer to keep company with their own, men and women who share their tastes, point of view, outlook on life.

These are sentiments so candid that I was surprised to find Mr. Gross expressing them. But he is now prepared to disown what he said. The club is just fine, and just look at those splendid greens! The admissions board is to be faulted only when, by accident or inadver-

tence, it excludes one of its own, a scientist who like L.V. Heilbrunn has *published in the literature*. Such men are entitled to wear the gold cufflinks with the crossed golf clubs; keeping *them* out would be irresponsible. But keeping out the others is not only good science but good sense. *Ipse dixit.*

A few other points deserve comment. In offering Nilsson and Pelger the oil of his approval, Mr. Gross affirms that I have misunderstood or misinterpreted critical elements of their paper. In keeping with his longstanding policy of never documenting his discontent, he does not say which elements. As I keep reminding him, this is not sporting. Still, it is inconceivably droll to see Mr. Gross excusing Richard Dawkins's misrepresentation of Nilsson and Pelger's work by appealing to the fact that Dawkins expressed his views in a *trade book*. Mr. Gross apparently believes that outside the country club, a man can say anything he wants, a policy that he would not dream of applying to critics of Darwin's theory.

A few of Mr. Gross's remarks suggest a need for remedial reading. I have never argued that "evolutionary theory cannot explain the eye." How on earth would I know *that?* And explain what in particular? Its emergence, its structure, its physiology, its biochemistry? What I contended specifically is that Nilsson and Pelger's paper is just nuts. Conspiracies and cover-ups are, in any case, not in my line, and I never suggested or supposed that evolutionary biologists who failed to criticize Richard Dawkins for misrepresenting Nilsson and Pelger did so as part of a conspiracy. Like *droshky* horses, they were only doing what comes naturally: turning a blind eye.

If the burden of Nilsson and Pelger's paper was to demonstrate the existence of "one possible evolutionary pathway to the geometry of a fish-like eye from a patch of photoresponsive cells," as Mr. Gross

writes, they have surely wasted their time. The existence of such a path is hardly in doubt. Every normal human being creates an eye from a patch of photoresponsive cells in nine months.

I certainly agree that the "only explanation we have for the structure of the eye . . . is Darwinian evolution." But neither an orchestra nor an explanation becomes good by being the only game in town.

On the other hand, I disagree that Darwin's theory is as "solid as any explanation in science." Disagree? I regard the claim as preposterous. Quantum electrodynamics is accurate to thirteen or so decimal places; so, too, general relativity. A leaf trembling in the wrong way would suffice to shatter either theory. What can Darwinian theory offer in comparison?

Finally, I would hardly dispute Mr. Gross's claim that "with the discovery of the developmental regulatory genes, we have learned how subtle, how versatile, and yet how simple the mechanism can be for transforming one biological structure to another." If he were to re-read the correspondence (COMMENTARY, September 1996) following the publication of my "The Deniable Darwin" (June 1996), he could not fail to be struck by my reply to his own letter, in which I specifically called attention to work on regulatory genes and eye formation—the very work that he now suggests I am keeping from my readers. Subtle and versatile, those genes? Yes, indeed. Absolutely astonishing? That, too. But hardly a triumph of Darwin's theory. For one thing, no Darwinian theorist had predicted the existence of these genes; for another, no Darwinian theorist has explained their emergence. The facts are simply far more fascinating than anything that poor drab Darwin, endlessly sifting time and chance, could possibly have imagined.

CITING THOSE ever useful but eternally anonymous "creationists,"

Matt Young argues yet again, as he did in our earlier exchange, that Nilsson and Pelger have given the lie to creationist claims. If it was their computer simulation that originally lent ardor to his asseverations, now it is their paper itself. Mr. Young is a man plainly prepared to rely on an endless series of fallback positions. In the end, he may have to argue that his refutation is its own best friend, and that Nilsson and Pelger's paper is itself superfluous.

No one doubts that the eye has evolved. Not me, in any event. Fish have eyes; rocks do not. Those eyes came from somewhere—right?—and if coming from somewhere counts as evolution, count me among its champions. No one doubts, furthermore, that the “eye could have evolved in 350,000 generations.” As I remarked earlier, the eye could have evolved in a weekend. The issue is whether it could have evolved in 350,000 generations *given the constraints of random variation and natural selection*.

I have absolutely no idea. Neither do Nilsson and Pelger. And neither does Matt Young.

Arguing now from the last trench before the bunker, Mr. Young writes that Nilsson and Pelger's paper deals with the development of *invertebrate* eyes, and triumphantly chides me for overlooking this point. On p. 56 of their paper, Nilsson and Pelger write: “After constriction of the aperture and the gradual formation of a lens, the final product becomes a focused camera-type eye with the geometry typical for aquatic animals (e.g. fish and cephalopods).” Fish are, of course, vertebrates, as anyone who has picked the flesh from a flounder knows. Perhaps I will be forgiven if I refer to this exchange as shooting fish in a barrel.

Making the point that the emergence of even the most modest eye will require simultaneous and parallel evolutionary development, Mr. Young asks that I defend my claim that this process could not have tak-

en place by quantitative steps. In the first place, I made no such claim, if only because its truth struck me as obvious. But were I to make such a claim I would observe, as Richard Dawkins does, that to the extent that simultaneous and parallel changes are required to form a complex organ, to that extent does the hypothesis of random variation and natural selection become implausible. It is one thing to find a single needle in a haystack, quite another to find a dozen needles in a dozen haystacks at precisely the same time. Surely the burden of proof in such matters is not mine. I am not obliged to defend such mathematical trivialities as the proposition that as independent events are multiplied in number, their joint probability of occurrence plummets.

I have no idea what Mr. Young means when he writes that the number 1.00005 is not a percentage. Every number can be expressed as a percent, and every percent is a pure number. But he gets half credit for spotting a slip: the figure of 1.00005 between parentheses on p. 33 in my text should have been .005. Mr. Nilsson, who also spotted the slip, gets the other half. Me? I blame my editors.

Finally, I did not fault the scientific community for failing to criticize Nilsson and Pelger's work. I did the job of criticism myself. I faulted the Darwinian community—Mr. Young included—for failing to denounce scientific fraud, specifically the misrepresentation of Nilsson and Pelger's work by Richard Dawkins. Now I see that Mr. Young feels I have manhandled him in these exchanges. Too bad. COMMENTARY is not some academic mouse hole.

**MARK PERAKH**, a *sensei* of the “noted scientists say” school of self-defense, is right in one respect: the computer simulation missing from Nilsson and Pelger's paper has no bearing on what they actually said and claimed. And right in a second respect: “The real question [is]

whether an eye could have developed in a geologically short time *via a Darwinian mechanism*” (emphasis added). But then, although quite confident that I am wrong in my criticisms, he offers nothing by way of rebuttal. Like so many of these martial-arts types, he is too busy preparing himself to run from the field with honor to bother doing battle.

Contrary to what Mr. Perakh asserts, not only can I imagine, I do not doubt, that “distinguished scientists,” many with a record of “substantial achievement,” can have an opinion different from my own. It happens all the time. I would not dream of accusing ten respected scientists of fraud simply because they passed on the opportunity to have a go at Nilsson and Pilger. The men and women I criticized earned my contempt the hard and dirty way, by saying nothing about scientific misconduct when it was right under their noses.

LIKE MR. PERAKH and Paul R. Gross, Jason Rosenhouse regards Richard Dawkins's misrepresentation of Nilsson and Pelger's work as a “minor error.” Some minor, some error. What, may I ask, is the difference between inventing data out of whole cloth and inventing a computer simulation out of whole cloth? Should not evolutionary biologists be held to the same standards as physicists? Or even journalists? What part of the declaration that fraud is fraud does he fail to endorse? These are not semantic issues. If I claimed in print that Mr. Rosenhouse has four eyes, his denials would not turn on what I meant. Two eyes, I am sure he would say, are not there. Two eyes, and one computer simulation.

Mr. Rosenhouse believes that Nilsson and Pelger made an important discovery: namely, “that there is a smooth gradient of increasing visual acuity linking a light-sensitive spot to a lens-bearing eye.” This is not their discovery, it is a restate-

ment of their chief assumption. "The model sequence is made," they write, "such that every part of it, no matter how small, results in an increase of the spatial information the eye can detect" (p. 53). Note: *made*, not discovered.

To repeat, the flaw in Nilsson and Pelger's work to which I attach the greatest importance is that, as a defense of Darwinian theory, it makes no mention of Darwinian principles. Those principles demand that biological change be driven first by random variation and then by natural selection. There are no random variations in Nilsson and Pelger's theory. Whatever else their light-sensitive cells may be doing, they are not throwing down dice or flipping coins to figure out where they are going next.

Mr. Rosenhouse's conviction that the randomly occurring changes required by Darwin's theory are nevertheless "plainly implied" throughout Nilsson and Pelger's paper owes nothing to the facts and little to common sense. If changes in their model were really random, their temporal estimates would be apt to change by orders of magnitude, a point I made in my essay and again in my reply to Dan-E. Nilsson above. In my essay I also questioned Nilsson and Pelger's decision to hold selection pressure constant over time. In this, I found myself echoing John Gillespie (*The Causes of Molecular Evolution*, 1991, p. 294). "[W]e must be concerned," Gillespie writes, "with models of selection in variable environments. How could it be otherwise? Natural selection is a force adapting species to their environments. Environments are in a constant state of flux; selection coefficients must be in a constant state of flux as well." What is good enough for Gillespie is good enough for me.

In approving of the value chosen by Nilsson and Pelger for selection pressure, Mr. Rosenhouse writes

that it is "judiciously low for almost any environment." Is it indeed? The figure that Mr. Rosenhouse calls ludicrous, Nilsson and Pelger term pessimistic, and Mr. Gross reasonable. The correct term is arbitrary—as in, it is anyone's guess what the variance among a bunch of fish might have been a couple of million years ago. Studies of variance and heredity typically deal with tiny populations and small periods of time. Studying the collared flycatcher, *Ficedula albicollis*, Merilla, Kruuk, and Sheldon collected eighteen years of data for 17,171 nestlings in order to reach some quite modest quantitative conclusions (J. Merilla, L.E.B. Kruuk, and B.C. Sheldon, "Natural Selection on the Genetic Component of Variance in Body Condition in a Wild Bird Population," *Journal of Evolutionary Biology* 14, pp. 918-921, 2001). Nilsson and Pelger's imaginary population ranges over space and time in a way that could not possibly be disciplined by the data.

NICK MATZKE believes that Nilsson and Pelger provide a mathematical model for the development of the eye. Let us be honest: beyond a few finger-counting exercises, there is no mathematics in their model, and while their references do contain some legitimate mathematics (nothing beyond second-semester calculus, but also nothing to sneeze at), their references, as I have shown in patient detail, do not support their theory. The task of modeling the eye's complicated geometry from light-sensitive cell to fully functioning eye is utterly and completely beyond our powers, as a glance at any textbook dealing with embryology would show.

Mr. Matzke devotes the greater part of his otherwise interesting letter to doing battle with various "creationist straw men." It is useful work, I am sure, the more so since the creationists are never named.

But whoever they are, I am not among them. Quite the contrary, I am as eager to do right by the snails as he is: why should he think otherwise? It is only when he passes to matters of fact that we part company.

Nilsson and Pelger's theory is intended to encompass the evolution of the eye in fish and cephalopods. Fish indisputably have bones, an attractive skull, and for the most part two staring eyes. The cephalochordate *Branchiostoma* (*Amphioxus* in a now out-of-date system of nomenclature) is widely taken by paleontologists to be a very plausible ancestral model to the vertebrates. It has certain vertebrate features while lacking others. These others include bones, a skull, a brain, and *paired sensory organs*: in other words, it has no eyes. Mr. Matzke's very confident assertion that cephalochordates have "primitive eyes" is simply untrue.

Now that I have swept away a few straw men of my own, let us see what is left to clean up. In my essay I wrote that Nilsson and Pelger made no attempt to discuss the cost-benefit payoffs associated with an improvement in visual acuity. My aim in discussing the reconstruction of the fish skull was not to argue that eyes came first *or* that bones did. Paired sensory organs *and* bones are characteristics of the vertebrates. Plainly they evolved together. Plainly, too, one function of the bony skull in vertebrates is to provide protection for the paired sensory organs located on their heads. The protection racket, as every Mafia boss is aware, does not come cheap; but Nilsson and Pelger, in adding up the benefits of visual acuity, did not ever bother to consider the vigorish. This is such an unobjectionable point that I cannot imagine why Mr. Matzke found it fishy.

I very much appreciate the letters from David Safir and Norman Gentieu.