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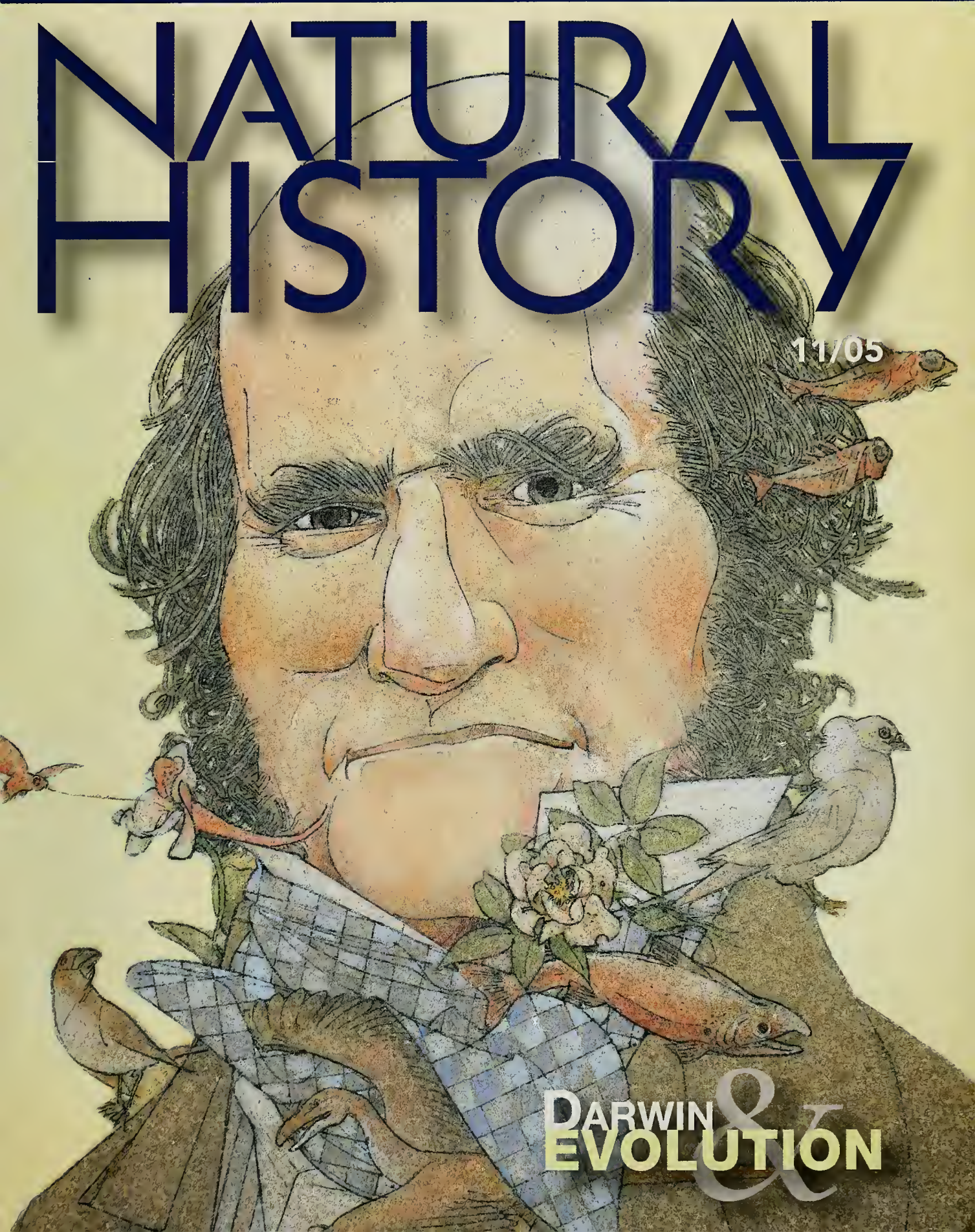

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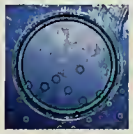

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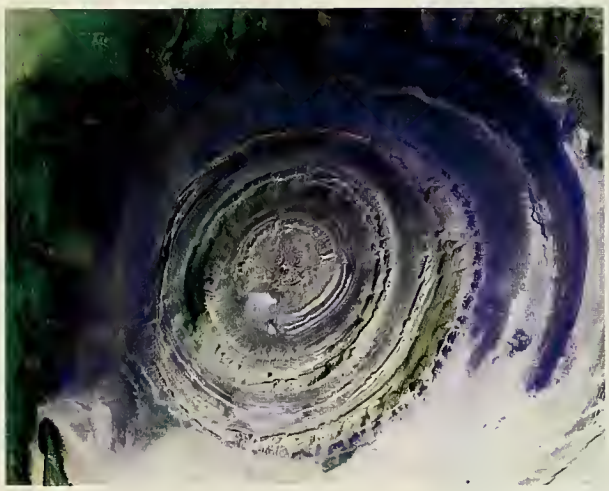

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Dr. Sylvia Earle's office covers two thirds of the Earth's surface. Her job title is a little more difficult to define. Marine biologist. Oceanographer. Botanist. Aquanaut. Explorer. And innovator. Above water, Dr. Earle has spent more than 40 years working to preserve the oceans. Beneath its surface, she's spent more than six thousand hours exploring, observing and cataloging things we never imagined existed. At 1,250 feet, she set a world record for the deepest, untethered, solo ocean dive. To most people, an accomplishment in itself. To Sylvia, it was just one more thing to do in the endless pursuit of science.

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THE NATURAL MOMENT

Beachcombing

Photograph by Tui De Roy

THE NATURAL MOMENT

◄ *See preceding two pages*

Sail to the Galápagos Islands, where Charles Darwin made his most famous discoveries, and you'll likely be met on the lava rocks near the water's edge by two stalwart creatures: the marine iguana and the sally lightfoot crab. Both species use their pointed claws not to hunt but to keep hold of the craggy shore. The crabs usually scavenge for leftovers, and the iguanas dive into the cold, current-prone Pacific for seaweed.

Photographer Tui De Roy caught the sally lightfoot pictured here as it gleaned a snack by picking dead skin off the iguana's head. Having come ashore to warm up after grazing, the reptile seemed unfazed, even pleased, by the exfoliation treatment. And the crab, no doubt, enjoyed its well-salted meal: marine iguanas expunge their excess salt in a spray of nasal rheum that often ends up encrusting their spiky crowns.

De Roy encountered the pair on Española, the oldest and most southerly island in the Galápagos. In true Darwinian form, the marine iguanas on Española are far more colorful than the same species on other islands in the chain. Recent studies have shown that these iguanas have an unusual adaptive trait: their skeletons can shrink when times are tough and regrow in times of plenty. Darwin, who described them as "disgusting" and "clumsy," may have been too dismissive when he clambered onto their turf. —*Erin Espelie*

UP FRONT

The New Darwinism

Evolutionary biology has always been the most controversial of the scientific disciplines. Darwin himself hesitated to bring his ideas to light, for fear of the misunderstanding and vitriol they might engender. His fears, of course, were justified. Richard Dawkins, in his introduction to this month's special section on "Darwin & Evolution" ("The Illusion of Design," page 35), diagnoses half of the "public relations" problem: Darwin's revolutionary theory of evolution by natural selection is too simple for its own good. How could something so straightforward explain anything so manifold as the origin of species? The other half of the problem is the subject matter: evolution treads on issues—the very origins of the human family—that arouse blood passions.

Many evolutionary biologists today have been as reticent as Darwin was to wade into public controversy. First, they will tell you, the controversy of interest to most people—the opposition of religious fundamentalists to Darwinism—lies outside science. Second, they will add, debating creationism, now rebranded and repositioned as "intelligent design," can only grant scientific legitimacy to a position that has gained none on its own. The late Stephen Jay Gould made the latter argument when this magazine assembled a forum on evolution and its critics nearly four years ago (for a transcript, visit our Web site at www.naturalhistorymag.com).

But Gould was anything but reticent about fighting back when it came to testifying in court against teaching creationism in public school science classes. Many evolutionists have at last concluded that Gould's aggressive stance must be extended beyond the courtroom. Too often, though, their counterattacks have been condescending. "Trust us," they say. "The evidence for evolution is overwhelming." But the reasons science deserves that trust, the positive case for evolution, have stayed far from the public eye.

The issue in your hands is intended to fill part of that void. The evidence for evolution *is* overwhelming, and as you read this issue, you'll soon appreciate why. The "new Darwinism" builds on classic Darwinian ideas, but its modern vigor derives from evidence that was unavailable, or even inconceivable, to Darwin himself:

- Evolution has now been directly observed in nature (for a quick list of examples, see the table on page 50).
- The fossil evidence in support of evolution is now abundant.
- The revolution in genetics, utterly undreamt of in Darwin's day, makes an irresistible case for the unity of life on Earth.

• • •

Darwin & Evolution," as its title implies, has two main parts. In "The Historical Darwin" (page 38), you'll find background on Charles Darwin, the man, that gives context and even poignancy to the origins of his theory. It also serves as a companion to a major exhibition titled "Darwin," which is opening at the American Museum of Natural History on November 19. In "Darwinism Today" (page 47), you'll find an intellectual smorgasbord, by some of the world's foremost experts and writers on evolutionary biology, on leading topics in the new Darwinism.

I am particularly grateful to Richard Milner, whose lifelong study of these issues have made him the ideal guest editor of the section.

—PETER BROWN

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Born in Belgium but raised in the Galápagos, **TUI DE ROY** ("Beachcombing," page 4) called the Galápagos home for more than forty years. She now lives in New Zealand but still serves as a board member of the Charles Darwin Foundation, which has its research station in the Galápagos. Her work as a photographer, writer, and conservationist is recognized worldwide. In early 2005, De Roy received the "Outstanding Nature Photographer Award" from the North American Nature Photography Association. Firefly Books released her latest book, *The Andes: As the Condor Flies*, this past October.

RICHARD DAWKINS ("The Illusion of Design," page 35), a world-renowned explicator of Darwinian evolution, is the Charles Simonyi Professor of the Public Understanding of Science at the University of Oxford, where he was educated. Dawkins's popular books about evolution and science include *The Selfish Gene* (Oxford University Press, 1976), *The Blind Watchmaker* (W.W. Norton, 1986), *Climbing Mount Improbable* (W.W. Norton, 1996), and most recently, *The Ancestor's Tale* (Houghton Mifflin, 2004), which retells the saga of evolution in a Chaucerian mode.

DAVID KOHN ("The Miraculous Season," page 38) became interested in Darwin's contributions to botany during graduate school, when he realized that Darwin's research on hermaphroditic flowering plants played a big part in the formation of his theory of evolution. Kohn is the Robert Fisher Oxnam Professor of Science and Society at Drew University, in Madison, New Jersey. He is also a general editor of the Darwin Manuscript Project, an online edition of Darwin's 80,000 folios of scientific notes, which will form part of the Darwin Digital Library of Evolution, sponsored by the American Museum of Natural History.

As an editor with the Darwin Correspondence Project, **SHEILA ANN DEAN** ("Bee Lines and Worm Burrows," page 40) has spent ten years compiling and editing letters to and from the renowned naturalist. Dean has just finished work on volume 15 of *The Correspondence of Charles Darwin*, which will be published in December by Cambridge University Press. This volume covers Darwin's correspondence for 1867, the year that he began work on *The Descent of Man, and Selection in Relation to Sex*.

RICHARD MILNER ("Darwin's Shrink," page 42) is the author of *The Encyclopedia of Evolution: Humanity's Search for Its Origins* (Henry Holt, 1993) and *Charles Darwin: Evolution of a Naturalist* (Facts on File, 1994). A contributing editor to *Natural History* and an associate in anthropology at the American Museum of Natural History in New York City, Milner also served as guest editor for this month's special section, "Darwin and Evolution." "Darwin's Shrink" is a tribute to Ralph Colp Jr., Milner's mentor in historical studies. Milner has performed his musical, *Charles Darwin: Live & In Concert*, all over the world; his book *Darwin's Universe* will be published in 2006 by the University of California Press.

A reader in the history of science and technology at The Open University, in the United Kingdom, **JAMES MOORE** ("Good Breeding," page 45) has studied Darwin for more than thirty years. He is currently working with the historian of science Adrian Desmond on a book about Darwin and race, and researching a biography of the English evolutionist Alfred Russel Wallace.

JONATHAN WEINER ("Evolution in Action," page 47) began writing about evolution in 1990, when he met Peter and Rosemary Grant, who observe evolution firsthand in finch populations in the Galápagos. Weiner's book *The Beak of the Finch* (Alfred A. Knopf) won a Pulitzer Prize in 1994. He is a professor in the Graduate School of Journalism at Columbia University, in New York City. He is also working on a book about human longevity for Ecco Press.

As a child, **DONALD R. PROTHERO** ("The Fossils Say Yes," page 52) became hooked on dinosaurs, and, as he says, he "never grew up." In college he began studying fossil mammals instead of dinosaurs, because the fossil record is more abundant for ancient mammals. Prothero is a professor of geology at Occidental College, in Los Angeles, and a lecturer in geobiology at Caltech. His current research focuses on North American fossil rhinoceroses, camels, and pronghorns.

SEAN B. CARROLL ("The Origins of Form," page 58) is a professor of molecular biology and genetics at the University of Wisconsin–Madison and an investigator with the Howard Hughes Medical Institute, in Chevy Chase, Maryland. His most recent book on the development and evolution of animal forms is *Endless Forms Most Beautiful: The New Science of Evo Devo* (W.W. Norton, 2005). Carroll is also the author of a book on evolution titled *The Making of the Fittest,* scheduled for publication by W.W. Norton in 2006.

Frequent childhood visits to the American Museum of Natural History, the Bronx Zoo, and the New York Botanical Garden laid the foundation for **DOUGLAS J. FUTUYMA** ("On Darwin's Shoulders," page 64) to become interested in the diversity of living organisms and in evolution as the cause of that diversity. Futuyma is a distinguished professor in the department of ecology and evolution at the State University of New York, in Stony Brook, and has done extensive fieldwork on insects and their host plants. His most recent book is a textbook titled *Evolution* (Sinauer Associates, 2005).

NILES ELDREDGE ("Patterns," page 80) is a curator in the division of paleontology at the American Museum of Natural History. A specialist in trilobites, his focus is on achieving a better fit between evolutionary theory and the historical patterns of stasis and change evident in the fossil record. He recently authored *Darwin: Discovering the Tree of Life* (W.W. Norton, 2005), a companion volume to the new Darwin exhibition he has curated at the museum.

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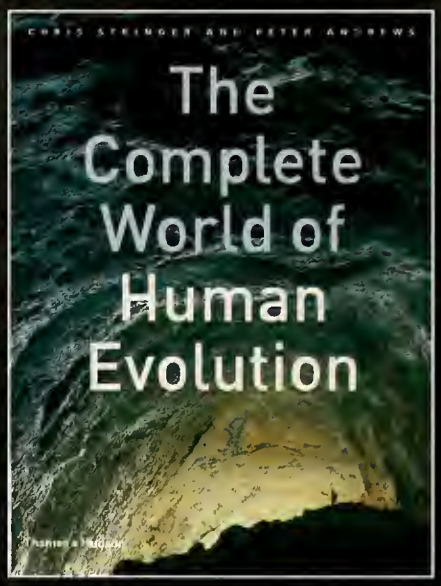

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Chris Stringer is Head of Human Origins at the Natural History Museum, London, and Peter Andrews formerly held the same position.

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Making Music

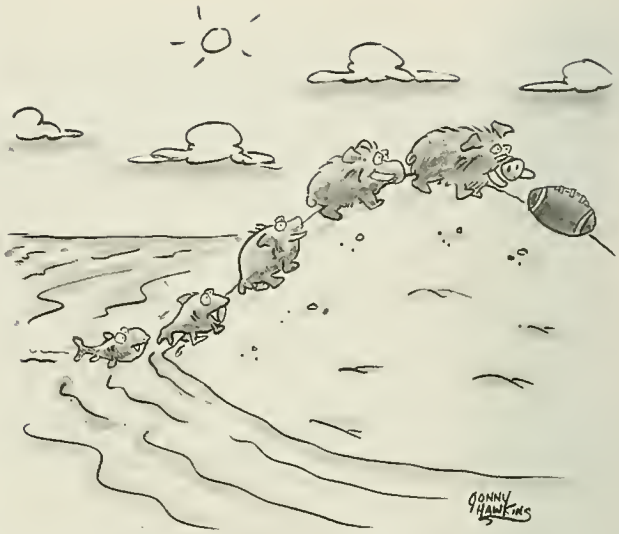
"The Magic Flutes" [9/05], by Zhang Juzhong and Lee Yun Kuen, was fascinating, but it does not discuss how the flutes were made. How did someone from the early Neolithic period cut fragile bones to size and drill holes in them? Do we have any knowledge of the tools they used? Did they use metals in addition to Stone Age tools?
Neil Towell
New York, New York

ZHANG JUZHONG AND LEE YUN KUEN REPLY: We can only infer how the flutes were made on the basis of the technologies available to the Jiahu people. There is no evidence that metal tools were used at the Jiahu site.

Although the red-crowned crane's bones were very thin, they were also very hard, so they wouldn't have broken easily. Cutting a crane bone at an exact location required precise control, which could be achieved by sawing with a stone knife. The holes in the flutes were perforated by drilling, and in fact, some stone drills were found in Jiahu, though they did not match the size of the holes in the flutes. The Jiahu may have used other stone drills that matched the holes, but we didn't uncover any during the excavation.

Bad Bugs

In her article on the assassin bug ["In The Heat of the Night" (7–8/05)], Graciela Flores falls into the inverse-square-law trap when she writes that the amount of heat received by a bug's antennae quadruples as the bug halves the distance to its prey. The inverse square law applies only when the heat source is a point.



When dealing with a distributed heat source, such as the heated plates used for the experiments in the article, the amount of heat received by the bug's sensors ceases to grow substantially once the distance from the insect to the heat source becomes smaller than the dimensions of the source. Perhaps it is this effect that the assassin bug uses to gauge its distance from a victim?
Philip L. Epstein
Monroe Township, New Jersey

GRACIELA FLORES REPLIES: Philip L. Epstein correctly points out that the inverse square law applies only to point sources. Although the thermal plates I used were certainly not points, they were smaller than the distance that separated them from the insects (though the illustration might have suggested otherwise). That makes the inverse square law a good working hypothesis.

The critical issue here is whether or not the increase in heat is inversely propor-

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tional to the distance to the heat source. Actually, the heat increases faster than the distance decreases, and vinchucas may be using this cue to learn their position relative to the heat source. It is also important to keep in mind that in the experiment described in the article, I was testing the ability of the vinchuca to estimate the area of the heat source, not its distance.

As Mr. Epstein suggests, it is theoretically possible that the heat received by the bugs' sensors becomes nearly constant as the distance from the insect to a massive heat source becomes very small. It is unlikely, however, that a vinchuca relies on that effect to gauge its distance from a host. Insects confronted with heat sources of different size always extend the proboscis at the same distance from the source.

Measure for Measure

I enjoyed Neil deGrasse Tyson's article on measurement ["The Long and Short of It," 4/05], but I was disappointed when he said of the Imperial units, "I'm in no hurry to see it all go." Whether you're doing carpentry, plumbing, or cooking, working with a measurement system involves more than just making simple measurements. It is very frustrating to have to deal with measurements in different units. Further complicating the issue is that the same property can be measured in different units, depending on context. In cooking, ingredients are expressed in teaspoons, tablespoons, ounces, pounds, and cups. Dietary labels and guidelines, however, use milligrams, grams, and liters.
Ernest L. Asten
San Francisco, California

Up here in legally metric Canada, the dust has long since settled from the switch to metric, and we are enjoying a hybrid version of the two systems. The liter and its fractions have vanquished quarts, pints, and gallons, while the pound is still holding its own in things such as produce. After a valiant effort to change recipes to milliliters, cookbooks have gone back to the old cups and teaspoons. Packaged foods and temperatures are fully metric, along with gasoline and posted speeds, but most people still use inches and feet. After the initial trauma of the change, the present state seems a comfortable compromise.
Nancy Gray
London, Ontario
Canada

NEIL DEGRASSE TYSON REPLIES: Ernest L. Asten's assumption that I find imperial units unsuited for science, but okay for everyday use, slightly misrepresents my point. Imperial units are

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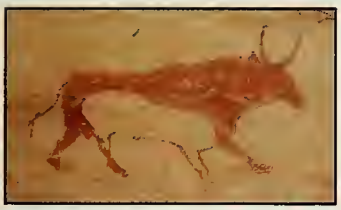

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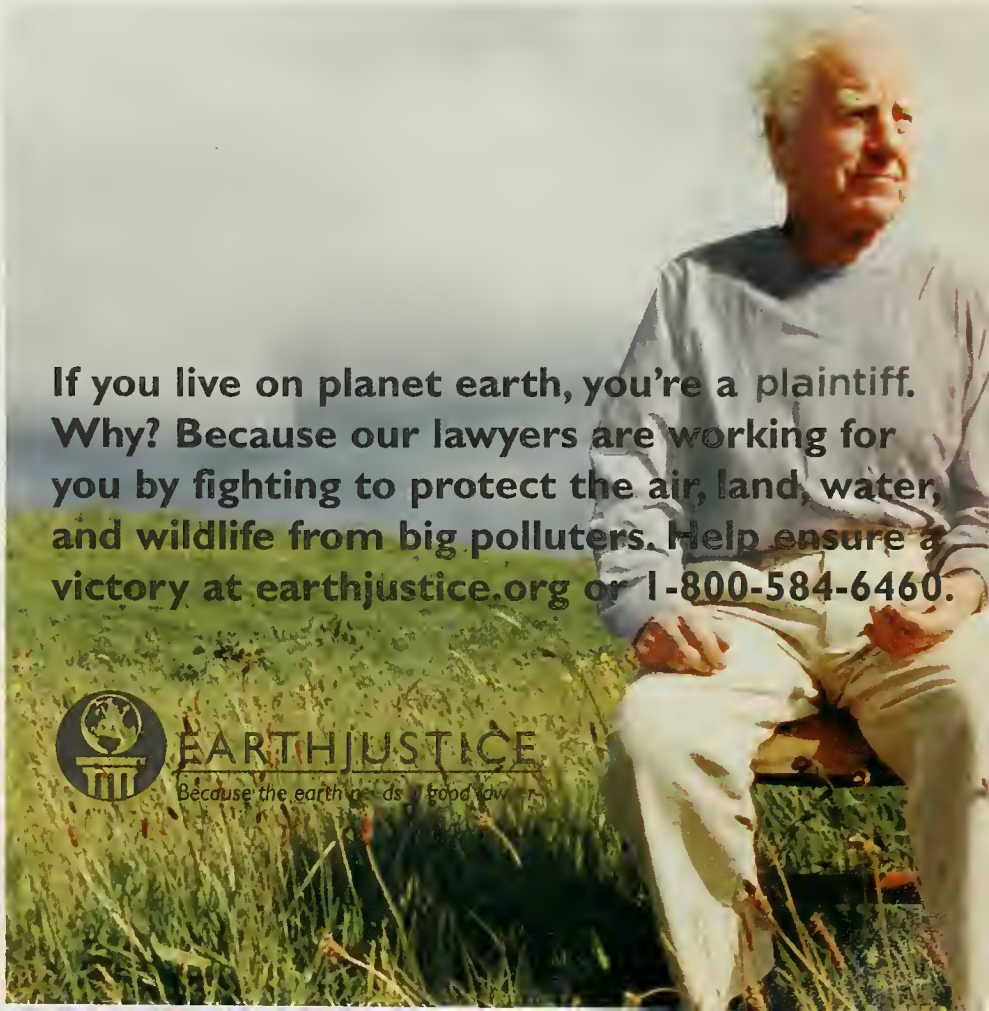


inappropriate for anything international, such as science. Most carpentry, plumbing, and cooking are local. So for these activities, and others, the forces to convert to metric are weaker, or even non-existent.

Hair Trigger

In his article on the Venus flytrap ["Snap!" 6-05], Adam Summers writes, "The flytrap features a set of inch-long, heart-shaped capture leaves, each fringed with trigger hairs. . . ."

The projections along the outer edges of both halves of the flytrap's leaves are not trigger hairs. But the real trigger hairs, or trichomes, are easy to miss: They grow on the inner surface of each leaf. The leaves close when a single trigger hair is bent twice consecutively or when two separate hairs are bent, each once, within a span of about twenty milliseconds.

William R. West
Burlington, North Carolina

Your *Theory* or Mine?

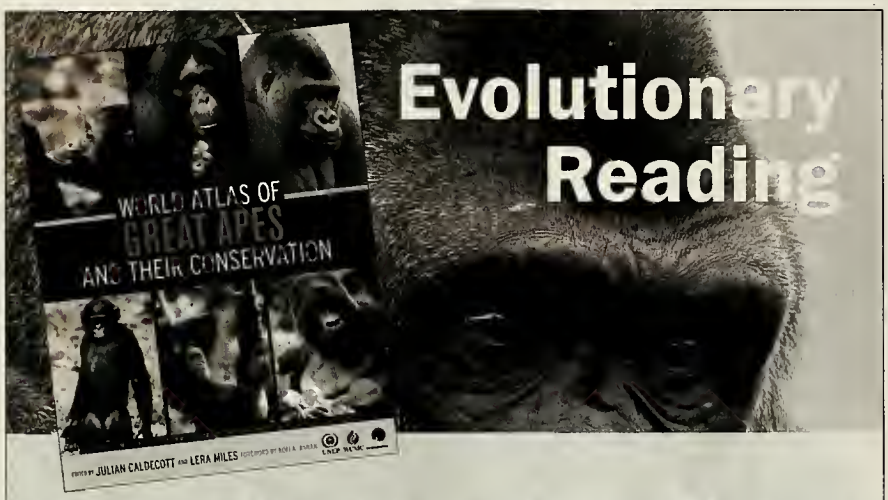
In his Up Front column "Prove It!" [9/05], Peter Brown argued that intelligent design is a problem because "it can't be tested, proved, refuted, or falsified." I agree. Nevertheless, in an advertisement a few pages later, you claim that intelligent design is "the theory that some have called the newest evolution of creationism." Intelligent design is not a theory, and your effort to draw readers to your Web site reeks of popular pandering that masquerades as journalism.

Albert Eibel
Louisville, Ohio

THE EDITORS REPLY: Isn't it interesting how "theory of intelligent design" comes so "trippingly on the tongue"? Surely that's just what the PR meisters of the I.D. movement intended, and we've fallen into their trap. But it gets worse. Through a clever bit of three-card monte with the word *theory*, I.D.'ers score two debater's points. First, they use it to label what is essentially a religious belief, subtly shifting the discussion into what sounds like scientific discourse. Then—watch my hands!—they reframe the connotation of the same word in the phrase "evolutionary *theory*": "After all, it's *only* a theory!"

The purpose of our ad, ironically, was to alert readers to a Web site discussing the very issues addressed by I.D. We thank Albert Eibel for bringing his point to our attention.

Natural History *welcomes correspondence from readers* (nhmag@naturalhistorymag.com). *All letters should include a daytime telephone number, and all letters may be edited for length and clarity.*



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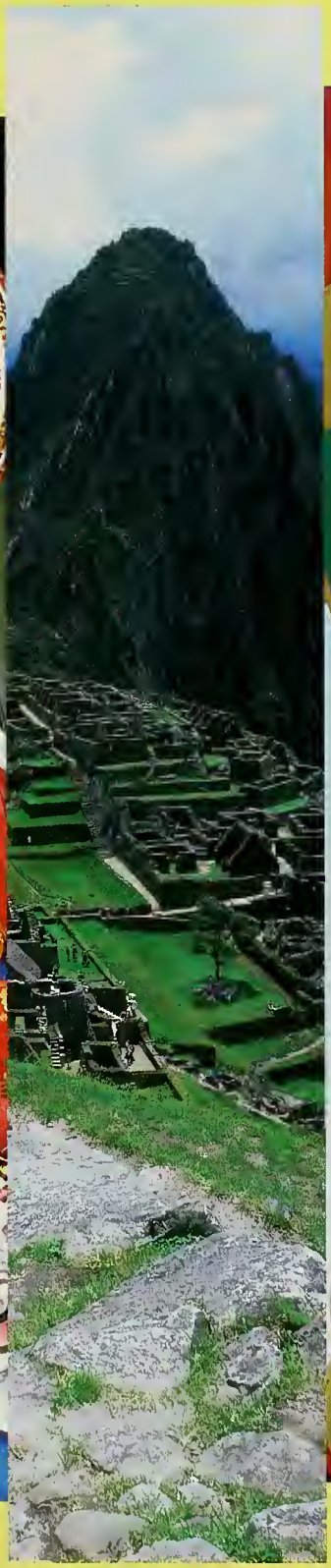

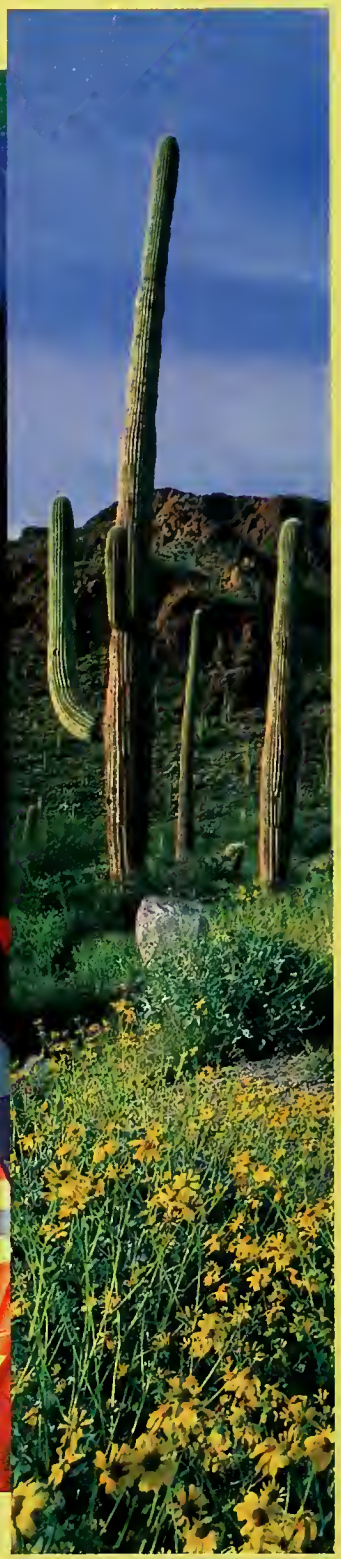

Landon's photo: Courtesy of the New Mexico Department of Tourism. Photograph by Dan Monaghan

Distinctive Destinations

From the Andes and the Himalayas, to the deserts of the American Southwest and the Seven Seas, a world of natural adventure awaits.

Incredible India–Incredible Wildlife

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EXOTIC, ACCESSIBLE INDIA IS HOME to one of the world's most vibrant cultures, bustling cities, glorious architecture, and, of course, the Taj Mahal. But savvy travellers seeking a singular experience know that India is equally known for its natural gifts: snow-clad peaks, crystal glaciers, rolling meadows, roaring rivers, impressive waterfalls, thick forests, fertile deltas, magical ocean beaches and moonscapes—all sources of inspiration and wonder.

Wildlife tourism is important to India; its national animal is the tiger, a symbol of strength and speed. Commitment to conservation of the world's most exotic animals and preservation of habitat is an integral part of India's consciousness. With 24 tiger reserves (60 percent of the planet's wild tigers live here), India is justifiably proud of Project Tiger, living proof that man can reclaim the natural habitat of these magnificent creatures. The shining gem of India's wildlife heritage is Bandhavgarh in Madhya Pradesh, where visitors can see Royal Bengal tigers, cheetahs, leopards, guar, sambhar and other iconic animals roaming free.

India is home to more than 70 national parks and 400 wildlife sanctuaries spread across the length and breadth of the country. Significant stops on the Indian Wildlife Circuit are Ranthambore National Park in Rajasthan, the Hazaribagh Wildlife Sanctuary in Bihar, and the Jim Corbett National Park in the foothills of the Himalayas. India abounds in forest areas crucial to endangered species—leopard, lion, Asiatic elephant, Bengal tiger and Siberian crane. The Himalayan region is home to elephant, deer, panther, wild ass, buffalo and snow leopards. India shelters 80 percent of the world's entire one-horned rhinoceros population; the Kaziranga Game Sanctuary is a must-stop for naturalists, environmentalists and wildlife travellers.

For birdwatchers, several hundred species call India home, including the rare narcondum hornbill, megapode, and griffon vulture. And the renowned Bharatpur Bird Sanctuary is not far from Delhi's urban bustle. . . yet another facet of surprising India!

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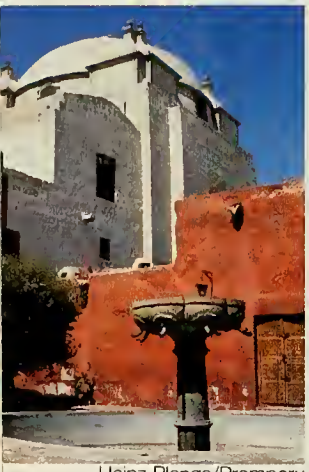
Peru's Hidden Legacy

A LAND OF NATURAL- AND MAN-MADE WONDERS



Heinz Plenge/Promperu

SAY "PERU," AND THE FIRST IMAGE that comes to mind is the spectacular buildings of Machu Picchu and the Inca empire. But this verdant, rugged country is also rich with archaeological sites from even more ancient times, when great civilizations bequeathed a legacy of their art, customs and rituals, their wisdom and skills. The Inca empire, in fact, lasted but a century and was a recent arrival in the 20,000 years of human occupation of Peruvian territory. Amazing architectural, cultural and artisanal gifts from all these periods endure to this day in the fabric of Peruvian life.

But in the beginning was the land, and discovering the natural bounty of Peru holds adventure and wonder for all who explore and discover it. The rugged Andes mountains, the lakes, forests, canyons and rivers, add up to one of the planet's most glorious and relatively untouched ecosystems. With 57 natural areas of conservation comprising 13 percent of the country, Peru has a legacy of environmental protection. Thousands of lakes and lagoons, rushing rivers carving breathtaking canyons, countless waterfalls cascading down from the Andes to rivers, lake and sea—Peru has all in abundance.

Here you can find 84 of the 104 life zones existing on earth, and Peru is home to more than 400 species of mammals, 300 reptiles, 1,700 birds and more than 50,000 plants.

> The country's astounding variety of climates and ecosystems ranks it among the world's top eight nations in biodiversity.

Lovers of adventure sports will find the Andes ideal for trekking, camping, mountain-climbing and hang-gliding with one of the world's most beautiful backdrops. The highlands are sprinkled with more than 15,000 lakes, snow-capped peaks soaring over 6,000 meters, the world's deepest canyons, bucolic valleys and picturesque villages. There are unparalleled opportunities for whitewater rafting, superb mountain biking trails, and, on the beaches of Paracas to the south and along the north coast, ideal surfing, windsurfing, scuba diving—and beachcombing.

Peru is for many the heart of South America's greatest civilizations. For those willing to look a little deeper, its combination of man-made glories and natural beauty make the country a must-visit.

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LAND · OF · THE · INKAS

The Secret Desert

TUCSON'S SUNSHINE AND SAGUAROS ARE JUST THE BEGINNING

TUCSON—THE OLDEST continuously inhabited settlement in the United States—embodies a rich Native American, Spanish, Mexican and American heritage. For those seeking spirit of place beyond the ordinary, the city's unique mix of cactus and cool has made it one of the world's top destinations.

From its beginnings in 1775 as a Spanish fortress, Tucson has been defined by the land. Set in the surprisingly verdant and versatile Sonoran Desert, ringed by five rugged mountain ranges and bathed in 300 days of sunshine each year, the "Old Pueblo" has long been a must-visit

for golfers, and sun/spa-seekers. But those who appreciate the city's commitment to preserve abundant desert plant and animal life discover another dimension. Bookended by expansive Saguaro National Monuments to east and west—Tucson is the only place in the world where these iconic, giant cacti not only grow but thrive—the city embraces its surroundings... with genuine outdoor experiences available even in the middle of town.

Tucson's Botanical Garden, named Best Secret Garden in America by *Reader's Digest* this year, gives a gracious introduction to the amazing variety of local plants. For flora *and* fauna, the far-from-secret Arizona-Sonora Desert Museum has been consistently voted one of the world's top ten zoos. More than a zoo, it is an internationally-acclaimed living ecosystem known for key desert research and preservation.

Tucson is home to the world's largest prestigious Gem, Mineral and Fossil Showcase, and La Fiesta de los Vaqueros is the nation's largest outdoor mid-winter rodeo.

Want to take a hike? Sabino Canyon, nestled in the Santa Catalina Mountain foothills, has miles of trails winding through cottonwood trees, streams, cactus and jagged cliffs. Glimpse many of the 250 native species of butterflies colorfully punctuating the landscape (and some of the world's largest number of hummingbirds).

At the end of the day, take in one of Tucson's legendary sunsets—preferably viewed from Gate's Pass, just 10 minutes from the city center—then look up. The skies above Tucson are so clear, thanks in part to groundbreaking light pollution ordinances, that every star seems close enough to touch. Tucson is the "Astronomy Capital of the World," for good reason: several world-renowned observatories call it home. Come see for yourself.

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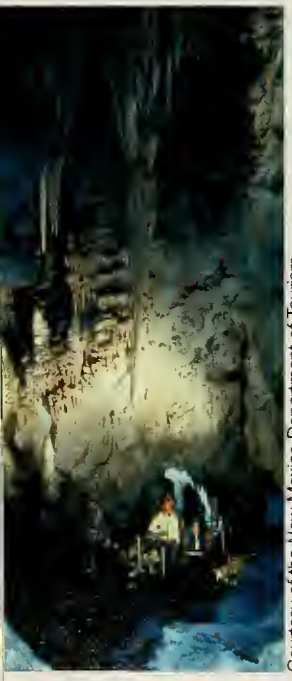
Unexpected New Mexico

A STATE OF NATURAL WONDERS



Courtesy of the New Mexico Department of Tourism

NEW MEXICO HAS ALWAYS BEEN A place where distinct cultures, traditions and talents abound. Civilizations dating back thousands of years—Spanish conquistadors in the 16th Century, and Anglo settlement in the 1800s—created a vibrant present-day cultural mix of residents who, along with visitors, celebrate the best of their individual cultures. New Mexico also has an astounding legacy of unique natural wonders.

New Mexico's 31 State Parks and Monuments embrace important man-made historic sites and preserve a dazzling array of environmental treasures, ensuring that the diverse history and pre-history of New Mexico is accessible to all for generations to come. The state's natural gifts range from lesser-known gems such as Spence Hot Springs—where visitors can take a dip in 100-degree natural pools high in the mountains—to the world-famous Carlsbad Caverns National Park, with 100 known caves dating back 250 million years and home to 300,000 Mexican free-tail bats. The Caverns' formations, including The Big Room—a gigantic subterranean chamber the size of eight football fields—draw visitors from around the globe.

At sea level, the world's largest gypsum dunefield at White Sands National Monument offers 275 square miles of glistening, ever-shifting dunes, rising to 60 feet in height. For out-of-this world landscapes, visit City of Rocks State Park, Tent Rocks National Monument and the Bisti Badlands. If volcanos are of interest, the spectacular El Malpais National Monument features a 17-mile-long lava tube system and ice caves formed as recently as 1,000 years ago. The Capulin Volcano National Monument, the core of a volcano active 10,000 years ago, is home to a wide variety of wildlife and plants. For something really, really old, the 15-mile-wide Valles Caldera National Preserve was formed by a collapsed volcano a million years ago.

At all of New Mexico's natural wonders, recreational opportunities abound, from hiking to auto touring, water sports to camping, backcountry and guided exploration. Visit the Land of Enchantment!

Courtesy of the New Mexico Department of Tourism. Photograph by Mark Nohl

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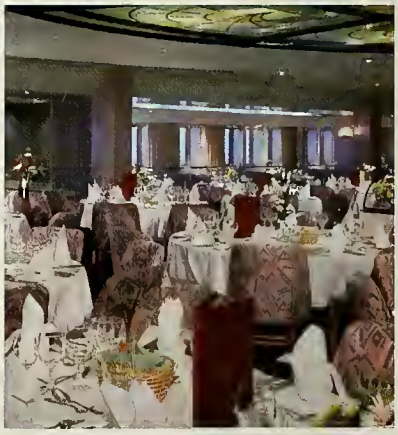
Learning in Luxury

A CRUISE LINE GIVES PASSENGERS THE GIFT OF TIME

ORIENT LINES, CELEBRATED FOR its comprehensive itineraries and good value, now in its 12th year, has carved out a top-notch reputation among discerning passengers who seek education along with destination. A tradition of friendly ambiance coupled with excellent service has made Orient Lines' 850-berth *Marco Polo* a favorite among sophisticated guests in the know. This autumn and winter, she will sail to ports in Norway, the Mediterranean, Greek Isles, Baltic, Scandinavia, Russia, South America and Antarctica.



Accomplished guest lecturers are on each cruise to enrich passenger understanding of the local culture and environment.

In a climate where vacations are becoming shorter and shorter, Orient Lines' success comes in part from bucking the trend. Because all of Orient Lines' vacations are designed as complete cruise-tours, ranging from 11 to 52 days, passengers are guaranteed a leisurely and in-depth experience seasoned travellers appreciate. And onboard gentleman hosts make sure everyone joins in the dancing and shipboard activities.

Orient Lines passengers enjoy first-class hotel stays, sightseeing in embarkation and disembarkation cities, transfers, baggage handling and the line's own hospitality desk wherever they go. With new itineraries being offered every year, and a series of exotic oceangoing voyages at special "2-for-1" rates, Orient Lines has ensured that passengers will see the world without having to hurry adventure and enrichment.

Discover the World

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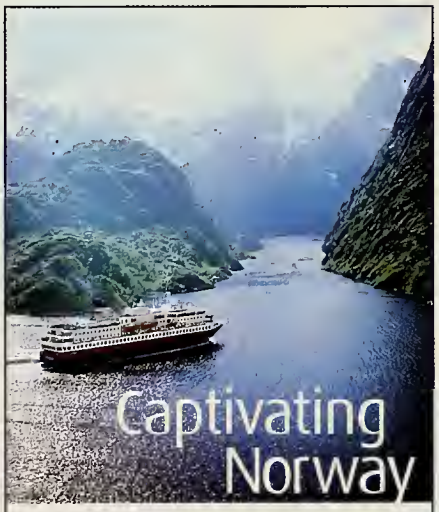
SMART TRAVELLERS HAVE ALWAYS EMBRACED THE IDEA OF seeing the world on a cruise, visiting exotic lands with the convenience of having one's hotel room move with you. And for 50 years, Swan Hellenic has been the leader in discovery travel for the seasoned, upscale passenger who seeks a learning experience and appreciates top-of-the-line comfort in the bargain. With destinations around the globe, from the well-known to the undiscovered, Swan Hellenic's concept of effortless exploration has brought its loyal guests a new dimension in travel.

A hallmark of Swan Hellenic's commitment to bringing adventure back to cruising is its award-winning program of distinguished guest speakers and inclusive shore excursions led by seasoned local guides. An appealing global destination mix, which includes "must see" places and hidden treasures, brings the excitement of travel to a more intimate and personal level, whether the destination be North America, Southern Africa, Europe, South America, the Middle East or the fjords of Scandinavia. Swan Hellenic's six-star-rated 694-passenger *Minerva II* sails the world with mega-ship luxuries and small-ship service and ambiance. Discriminating travellers appreciate the company's all-inclusive policy, too: everything from meals, transfers and shore excursions are included in the fare.



With its majestic fjords, dramatic arctic landscapes, and picturesque ports, Norway's west coast is a stunning stretch of scenery. And you can discover it all on a *Norwegian Coastal Voyage*. AARP members and Seniors 67+ enjoy special savings on most sailings.

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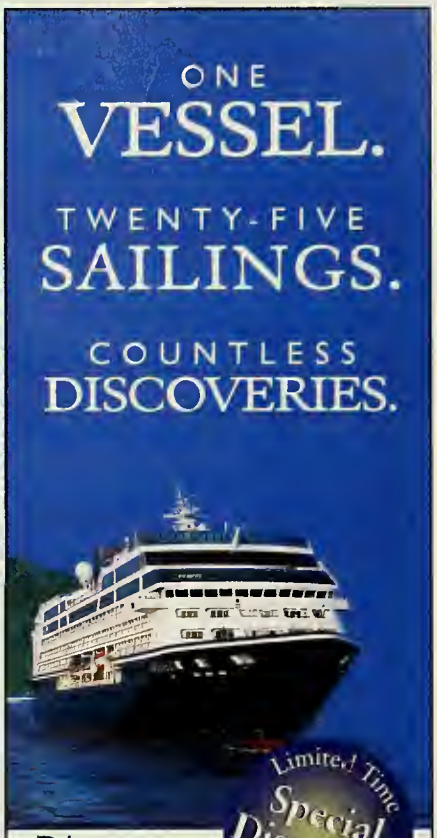

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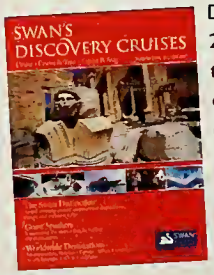

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Short-Listed

Saturn's small, icy moon Enceladus already holds the title of most reflective object in the solar system. Now it's vying for a spot on another select roster. Recent images made by the *Cassini* spacecraft show four eighty-mile-long fractures across Enceladus's south pole. The fractures appear to be actively venting, making the moon one of just a few celestial objects known to be geophysically active.

The vents eject water vapor and powdery ice particles from Enceladus's interior into space. A fresh—or perhaps freshly exposed—layer of ice coats the vents. So the vents must be either quite warm, quite young—likely between just ten and a thousand years old—or both. In fact, the moon's south pole is about twenty Celsius degrees warmer (thirty-six Fahrenheit degrees) than the *Cassini* scientists expected—though it's still a chilly –297.4 degrees F.

Data from *Cassini* indicate the venting could be driven by pressurized vapor from liquid water or warm ice beneath the moon's surface. But the moon's source of heat remains a mystery. Radioactive decay may account for some of it. Other moons in the solar system, notably Jupiter's moon Europa, are heated by friction, as the periodic change in the force of gravity stretches and flexes the interior with each revolution in an eccentric orbit. But Enceladus's orbit isn't eccentric enough to yield a lot of such "tidal heating." Nor does the moon definitively possess enough ammonia to lower the melting point of water.

Nevertheless, along with the water vapor, *Cassini* detected carbon dioxide and organic compounds such as methane. Those ingredients place Enceladus on yet another short, exclusive list: extraterrestrial sites that might harbor life. —*Jennifer Evans*

You Can't Tell a Tortoise by Its Cover

In 1835, as he surveyed the flora and fauna of the Galápagos archipelago, the young Charles Darwin was struck by how the shapes of the giant tortoises, *Geochelone nigra*, vary from island to island. The reptiles' shells are their most distinguishing trait, and so served as a major basis for their original classification into fifteen different taxa (eleven of which survive today). Now taxonomists and evolutionary biologists are taking a second look at the tortoises for reclassification purposes, this time via DNA . They've discovered that the tortoises of Santa Cruz, one of the main Galápagos islands, are even more diverse than their shells alone would suggest.

Galápagos tortoise on Santa Cruz island

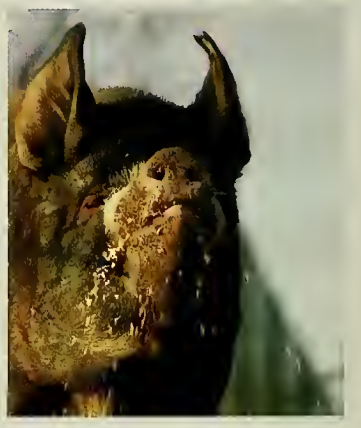
Michael Russello, an evolutionary biologist at Yale University, and his colleagues found that the three populations of giant tortoises living on Santa Cruz do not comprise one single taxon, as was previously thought. The populations are distinct enough to be split into at least two taxa—a key factor in their conservation status. (*Proc. Roy. Soc. Lond. Biology Letters* 1:287–90, 2005) —*Graciela Flores*

Happy Farmers

How much can a bit of sleuthing glean from a few ancient bones? Sometimes, the answer is, a lot. For one thing, anthropologists can get a pretty good idea, from traces of various elements in the bones, what their original owners ate. An abundance of the isotope carbon-13 indicates a diet rich in plants that build sugar molecules out of compounds containing four rather than three carbon atoms—known as "C4" photosynthesis. The relative proportion of the nitrogen-15 isotope reflects the diet's protein content. By analyzing the ratios of various isotopes, Ekaterina A. Pechenkina, an anthropologist at the City University of New York, and her collaborators inferred diets of peasant farmers—along with the diets of the farmers' pigs and dogs—who lived in northern China's Yellow River basin between 4,000 and 7,000 years ago.

The investigators determined that the farmers cultivated and consumed a tremendous amount of millet, the region's only C4 crop plant. And surprisingly, the animals ate even more of the grain: it comprised as much as 90 percent of their diets. That suggests the pigs not only dined on millet-bearing human refuse—stems and leaves, table scraps, and feces—but were also fed the grain directly. The dogs ate millet, too, and likely boosted their overall intake of it by hunting millet-eating mice.

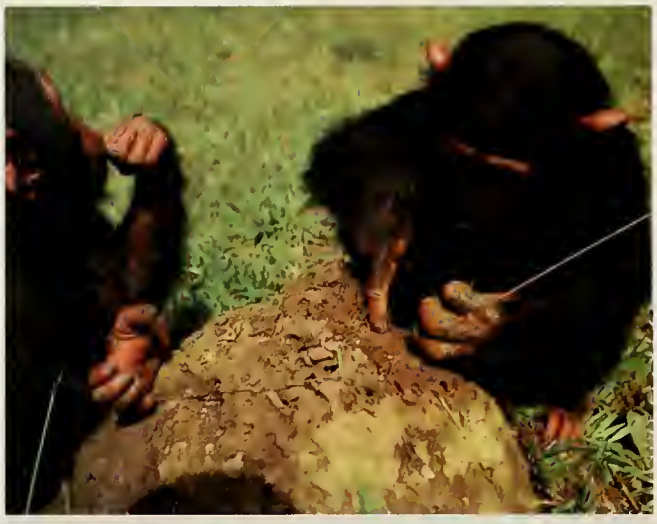
Grain-fed animals signal a well-off farming community that can afford to lose most of the grain's caloric value by using it to fatten up animals. If the farmers didn't regularly dine on pork, they may, at least, have raised the pigs for special occasions, such as ritual sacrifices or feasts. (*Journal of Archaeological Science* 32:1176–1189, 2005) —*Stéphan Reebs*



Mommy Training

In 1960 Jane Goodall watched a chimpanzee strip the leaves off a twig and then insert it into a termite mound to "fish" for termites. Her observation was the first time anyone documented seeing a nonhuman animal manufacture a tool in the wild. Termite fishing remains a favorite pastime among chimpanzees, because termites are a preferred source of protein for these apes. In Gombe National Park, Tanzania, all chimpanzees learn to fish for termites by age five and a half.

Now it seems that chimpanzees share something more than toolmaking with their human cousins. Chimpanzees may exhibit sex differences in learning, just as human children do. Elizabeth Lonsdorf, an animal behaviorist at Lincoln Park Zoo in Chicago, observed that female chimpanzees learn how to fish for termites much earlier—some twenty-seven months earlier, on average—than males. By age eighteen months, daughters spent a quarter of their time at the termite mound watching their mothers termite-fish. Sons of the same age were much more likely to spend their time near the mound playing.



Young chimpanzees in Kenya "fish" for termite treats.

Differences in how the sexes learn to termite-fish probably have their roots in evolutionary payoffs: for female chimpanzees, food resources are a top priority in order to reproduce; for males, access to mates is critical. So the females have to do their homework on termite fishing if they are to learn how to provide for themselves and for their nursing offspring. The males must spend more time studying how to climb the social ladder and build alliances so that they can attract mates in the future.

Whoever said fishing was for boys? (*Animal Behaviour* **70**:673–683, 2005)

—*Nick Atkinson*

It's Snot Raining

In the deep sea, where it's too dark for photosynthesis, the water teems with crabs, fish, jellyfish, mollusks, and other life-forms. But what do all those hungry mouths eat? Some eat each other, of course, as well as the nutrients raining down from above. Trouble was, the amount of available food, biologists reckoned, wouldn't come close to sating the creatures of the deep.

After ten years patrolling the waters off California's Monterey Bay with remote-control submarines, Bruce H. Robison, a marine biologist, and his colleagues at the Monterey Bay Aquarium Research Institute, have proposed a solution to the mystery. Small mid-water animals called larvaceans cast off nets of mucus, or "sinkers," which, by Robison's estimates, account for the deep-sea food deficit.

The larvaceans—free-floating sea squirts that look a bit like tadpoles—live inside the diaphanous mucus nets. The larvaceans make their nets to filter food particles from the water. When the filter clogs, the larvacean inside sheds it and makes another. Meanwhile, the discarded filter collapses and quickly sinks to the sea floor, carrying with it the larvacean's nutritious leftovers. Biologists had never factored in the sinkers because they disintegrate so quickly.

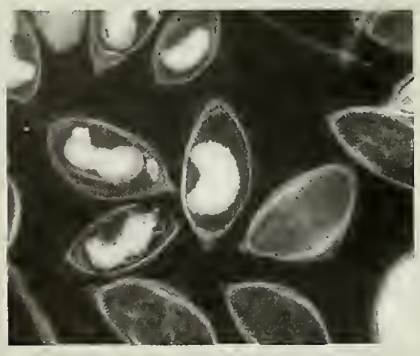
Robison's findings may also help climatologists model the atmospheric carbon cycle. Sinkers act, quite literally, as carbon sinks, bearing the element to the deep sea where it can remain for eons. (*Science* **308**: 1609–1611)

—*Rebecca E. Kessler*

Tree Impostors

Some parasites are content simply to feed off their host. But the most intriguing parasites also manipulate the host's physiology to their own ends. Recently, the first example of an insect parasite that takes control of seed development in a plant was described by a Franco-Canadian team of botanists led by Patrick von Aderkas of the University of Victoria in British Columbia.

When pollen fertilizes an ovule—the structure containing egg cells—the ovule begins to develop into a seed. While a plant embryo forms inside it, the ovule accumulates nutrients. Many parasitic insects lay their eggs in fertilized ovules so that their young can feed on the starches, fats, and proteins within. The tiny wasp *Megastigmus spermotrophus*, however, is strangely ahead of the game. It lays its eggs in Douglas fir ovules even before they are fertilized. This tactic seems risky, because not all ovules get fertilized, and the unfertilized ones abort without storing nutrients.

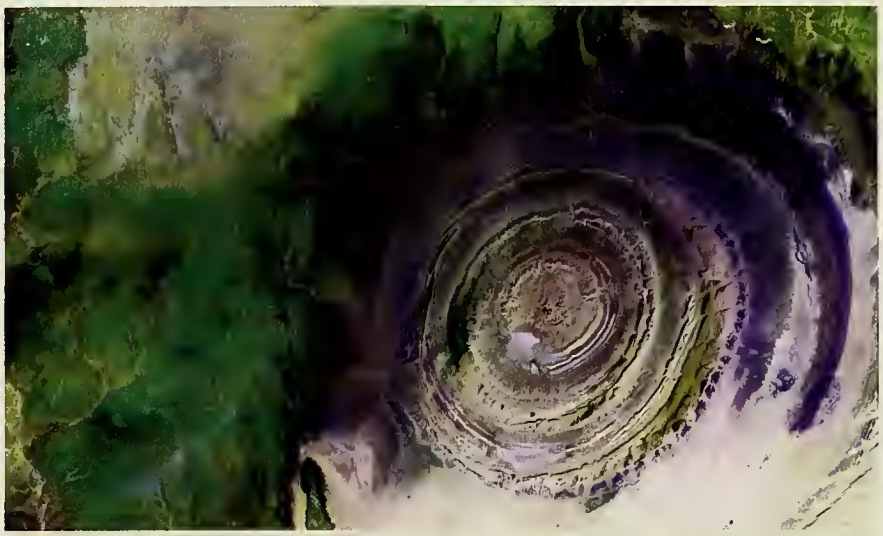


Parasitic larvae of the wasp Magastigmus spermotrophus, *each about three-sixteenths of an inch long, have taken up residence in some of the Douglas fir seeds shown in an X-ray image.*

But von Aderkas and his collaborators have shown that once the wasp egg hatches inside a would-be seed, the parasitic wasp larva somehow commandeers the tree's reproductive mechanism. The ovule then gets tricked into building up a nutrient reserve whether it is fertilized or not.

It turns out that several other species of *Megastigmus* induce plants to make galls—knobby "tumors" or other structures of plant tissue that shelter and feed invading insects. The botanists suggest that a similar mechanism may be at work here, though its exact nature is still unknown. (*Proceedings of the Royal Society B*, **272**:1491-1496)

—*S.R.*



Richat structure, often called the "eye of Africa," in western Mauritania

Eye on the Eye

The Richat structure lies in western Mauritania, surrounded by the vast Sahara. It includes a 650-foot-high plateau surrounded by concentric ridges and valleys, which together make up a dome structure some twenty-five miles across, perhaps best seen from the air. In fact, *Gemini* astronauts in the 1960s were the first to get a bird's-eye view of the structure, and ever since it has served as a landmark for space crews. They, among others, refer to it as the "eye of Africa."

Geologists have puzzled over the origins of the "eye" because of the plateau's unusual composition—it's an extraordinarily large (two miles wide by 130 feet thick) chunk of breccia, a kind of rock made up of smaller rocks cemented together. Was the Richat structure formed by the impact of a meteor? Or by shifting bedrock? Geologists Guillaume Matton and Michel Jébrak of the University of Quebec in Montreal, and James K.W. Lee of Queen's University in Kingston, Ontario, recently proposed a solution to the Richat enigma.

After extensive geophysical and mineralogical analysis, the geologists concluded that the 100-million-year-old structure has, for starters, volcanic origins. They think it formed when a magma-filled chamber developed deep underground, causing the earth's crust above it to bulge and fill with hot fluid. The fluid dissolved limestone in the crust, leaving caves behind and causing overhead rock to collapse. The entire mess eventually hardened into the central breccia formation. Erosion subsequently carved out the concentric ridges and valleys.

One feature of the Richat continues to stump the geologists: typically volcanoes occur in groups. The Richat, however, stands alone. (*Geology* 33:665–668, 2005) —*R.K.*

Silent Defense

Immunologists studying the HIV virus have been so busy deciphering the response it evokes in humans that they have missed a simple, ancient line of defense: RNA "silencing."

Silencing is a form of nucleic-acid-based immunity, originally discovered in plants. When an infected cell is alerted to an intrusion of an RNA virus, the cell triggers an enzyme to cleave the viral RNA into fragments. The fragments can then stop the virus from replicating by binding to and interfering with the expression of the viral gene products, rendering the virus harmless.

Until now, though, antiviral silencing had not been observed in mammals. Kuan-Teh Jeang, a virologist at the National Institute of Allergy and Infectious Diseases in Bethesda, Maryland, and his colleagues tested whether the process is part of the repertoire of human immunity. The results were most rewarding. Not only did the team spot spontaneous RNA silencing, they also found that the HIV virus has counter-defenses.

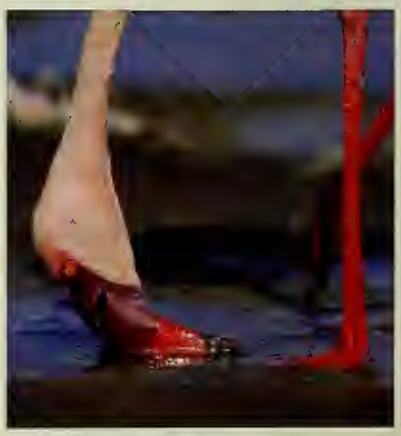
Intriguingly, the RNA sequences in HIV that elicit RNA silencing don't change much over time, in contrast to the rest of the HIV genome. Perhaps the ever-mutating virus has a constant Achilles heel, after all? (*Immunity* 22:607–19, 2005) —*G.F.*

Sideways Glance

If you could redesign your own head, where would you put your eyes? The question isn't entirely frivolous. To see in three-dimensions, and so to gauge distances effectively, your two eyes must face forward. But binocular vision comes at a price: it leaves a dangerous blind spot behind the head, which can give predators an advantage. The alternative is to place one eye on each side of your head. That can give you all-around vision, but it diminishes distance perception.

The way an animal catches its food usually settles the dilemma. Apes, cats, raptors, and the like that catch live, fast-moving prey tend to have forward-facing eyes. Aardvarks, rabbits, zebras, and other animals that rely on a more sedentary diet opt for eyes on each side of the head, maximizing their ability to spot lurking dangers. Why then, asked a team of British ornithologists, led by Graham Martin of the University of Birmingham, in England, does Africa's filter-feeding lesser flamingo have eyes that face forward? After all, the bird dines with its head upside down, which means that its eyes are pointing backwards.

It seems that for lesser flamingos there is more to life than filtering diatoms and algae from the mud. Unlike filter-feeding ducks, which raise self-feeding chicks, lesser flamingos must feed their young for the first ten to twelve weeks of their lives. The task requires accurate delivery of "crop milk" from parent to chick, directly into the chick's open mouth. Martin's team suggests that is possible only with forward facing eyes. (*Naturwissenschaften*, forthcoming) —*N.A.*



Lesser flamingo feeding in Lake Nakuru, Kenya

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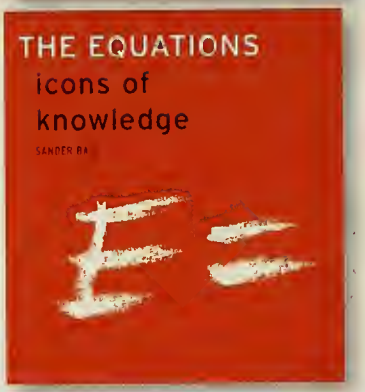

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The Perimeter of Ignorance

A boundary where scientists face a choice: invoke a deity or continue the quest for knowledge

By Neil deGrasse Tyson

Joseph Wright of Derby, *The Alchemist*, 1770 (detail)

Writing in centuries past, many scientists felt compelled to wax poetic about cosmic mysteries and God's handiwork. Perhaps one should not be surprised at this: most scientists back then, as well as many scientists today, identify themselves as spiritually devout.

But a careful reading of older texts, particularly those concerned with the universe itself, shows that the authors invoke divinity only when they reach the boundaries of their understanding. They appeal to a higher power only when staring into the ocean of their own ignorance. They call on God only from the lonely and precarious edge of incomprehension. Where they feel certain about their explanations, however, God gets hardly a mention.

Let's start at the top. Isaac Newton was one of the greatest intellects the world has ever seen. His laws of motion and his universal law of gravitation, conceived in the mid-seventeenth century, account for cosmic phenomena that had eluded philosophers for millennia. Through those laws, one could understand the gravitational attraction of bodies in a system, and thus come to understand orbits.

Newton's law of gravity enables you to calculate the force of attraction between any two objects. If you introduce a third object, then each one attracts the other two, and the orbits they trace become much harder to compute. Add another object, and another, and another, and soon you have the planets in our solar system. Earth and the Sun pull on each other, but Jupiter also pulls on Earth, Saturn pulls on Earth, Mars pulls on Earth, Jupiter pulls on Saturn, Saturn pulls on Mars, and on and on.

Newton feared that all this pulling would render the orbits in the solar system unstable. His equations indicated that the planets should long ago have either fallen into the Sun or flown the coop—leaving the Sun, in either case, devoid of planets. Yet the solar system, as well as the larger cosmos, appeared to be the very model of order and durability. So Newton, in his greatest work, the *Principia*, concludes that God must occasionally step in and make things right:

> The six primary Planets are revolv'd about the Sun, in circles concentric with the Sun, and with motions directed towards the same parts, and almost in the same plane. . . . But it is not to be conceived that mere mechanical causes could give birth to so many regular motions. . . . This most beautiful System of the Sun, Planets, and Comets, could only proceed from the counsel and dominion of an intelligent and powerful Being.

In the *Principia*, Newton distinguishes between hypotheses and experimental philosophy, and declares, "Hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy." What he wants is

data, "inferr'd from the phænomena." But in the absence of data, at the border between what he could explain and what he could only honor—the causes he could identify and those he could not—Newton rapturously invokes God:

> Eternal and Infinite, Omnipotent and Omniscient; . . . he governs all things, and knows all things that are or can be done. . . . We know him only by his most wise and excellent contrivances of things, and final causes; we admire him for his perfections; but we reverence and adore him on account of his dominion.

A century later, the French astronomer and mathematician Pierre-Simon de Laplace confronted Newton's dilemma of unstable orbits head-on. Rather than view the mysterious stability of the solar system as the unknowable work of God, Laplace declared it a scientific challenge. In his multipart masterpiece, *Mécanique Céleste,* the first volume of which appeared in 1798, Laplace demonstrates that the solar system is stable over periods of time longer than Newton could predict. To do so, Laplace pioneered a new kind of mathematics called perturbation theory, which enabled him to examine the cumulative effects of many small forces. According to an oft-repeated but probably embellished account, when Laplace gave a copy of *Mécanique Céleste* to his physics-literate friend Napoleon Bonaparte, Napoleon asked him what role God played in the construction and regulation of the heavens. "Sire," Laplace replied, "I have no need of that hypothesis."

Laplace notwithstanding, plenty of scientists besides Newton have called on God—or the gods—wherever their comprehension fades to ignorance. Consider the second-century A.D. Alexandrian astronomer Ptolemy. Armed with a description, but no real understanding, of what the planets were doing up there, he could not contain his religious fervor:

> I know that I am mortal by nature, and ephemeral; but when I trace, at my pleasure, the windings to and fro of the heavenly bodies, I no longer touch Earth with my feet: I stand in the presence of Zeus himself and take my fill of ambrosia.

Or consider the seventeenth-century Dutch astronomer Christiaan Huygens, whose achievements include constructing the first working pendulum clock and discovering the rings of Saturn. In his charming book *The Celestial Worlds Discover'd,* posthumously published in 1696, most of the opening chapter celebrates all that was then known of planetary orbits, shapes, and sizes, as well as the planets' relative brightness and presumed rockiness. The book even includes foldout charts illustrating the structure of the solar system. God is absent from this discussion—even though a mere century earlier, before Newton's achievements, planetary orbits were supreme mysteries.

Celestial Worlds also brims with speculations about life in the solar system, and that's where Huygens raises questions to which he has no answer. That's where he mentions the biological conundrums of the day, such as the origin of life's complexity. And sure enough, because seventeenth-century physics was more advanced than seventeenth-century biology, Huygens invokes the hand of God only when he talks about biology:

> I suppose no body will deny but that there's somewhat more of Contrivance, somewhat more of Miracle in the production and growth of Plants and Animals than in lifeless heaps of inanimate Bodies. . . . For the finger of God, and the Wisdom of Divine Providence, is in them much more clearly manifested than in the other.

Today secular philosophers call that kind of divine invocation "God of the gaps"—which comes in handy, because there has never been a shortage of gaps in people's knowledge.

As reverent as Newton, Huygens, and other great scientists of earlier centuries may have been, they were also empiricists. They did not retreat from the conclusions their evidence forced them to draw, and when their

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discoveries conflicted with prevailing articles of faith, they upheld the discoveries. That doesn't mean it was easy: sometimes they met fierce opposition, as did Galileo, who had to defend his telescopic evidence against formidable objections drawn from both scripture and "common" sense.

Galileo quotes a church official saying that the Bible "tells you how to go to heaven, not how the heavens go."

Galileo clearly distinguished the role of religion from the role of science. To him, religion was the service of God and the salvation of souls, whereas science was the source of exact observations and demonstrated truths. In a long, famous, bristly letter written in the summer of 1615 to the Grand Duchess Christina of Tuscany (but, like so many epistles of the day, circulated among the literati), he quotes, in his own defense, an unnamed yet sympathetic church official saying that the Bible "tells you how to go to heaven, not how the heavens go."

The letter to the duchess leaves no doubt about where Galileo stood on the literal word of the Holy Writ:

> In expounding the Bible if one were always to confine oneself to the unadorned grammatical meaning, one might fall into error. . . .
>
> Nothing physical which . . . demonstrations prove to us, ought to be called in question (much less condemned) upon the testimony of biblical passages which may have some different meaning beneath their words. . . .
>
> I do not feel obliged to believe that the same God who has endowed us with senses, reason and intellect has intended us to forgo their use.

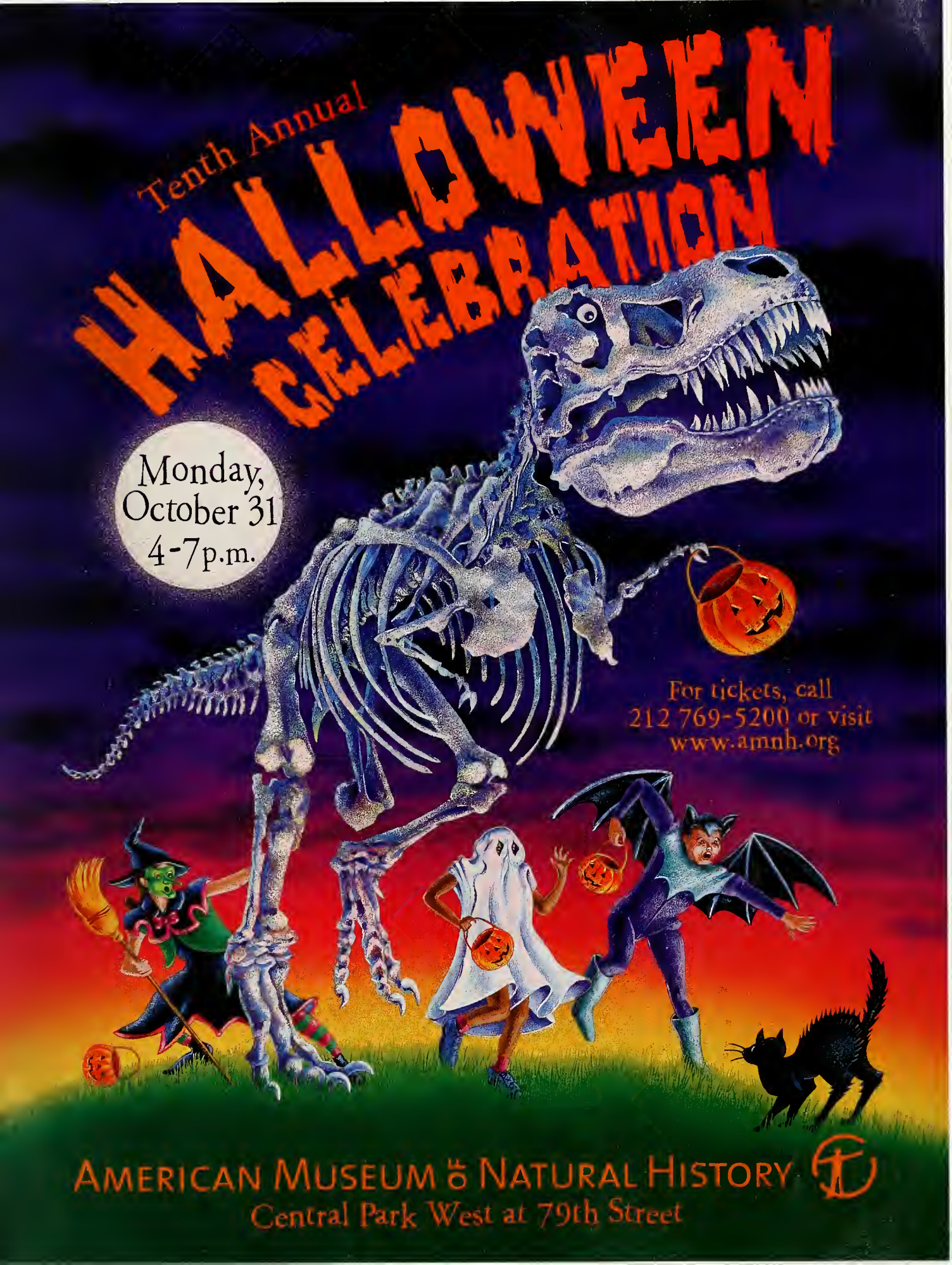
A rare exception among scientists, Galileo saw the unknown as a place to explore rather than as an eternal mystery controlled by the hand of God.

As long as the celestial sphere was generally regarded as the domain of the divine, the fact that mere mortals could not explain its workings could safely be cited as proof of the higher wisdom and power of God. But beginning in the sixteenth century, the work of Copernicus, Kepler, Galileo, and Newton—not to mention Maxwell, Heisenberg, Einstein, and everybody else who discovered fundamental laws of physics—provided rational explanations for an increasing range of phenomena. Little by little, the universe was subjected to the methods and tools of science, and became a demonstrably knowable place.

Then, in what amounts to a stunning yet unheralded philosophical inversion, throngs of ecclesiastics and scholars began to declare that it was the laws of physics themselves that served as proof of the wisdom and power of God.

One popular theme of the seventeenth and eighteenth centuries was the "clockwork universe"—an ordered, rational, predictable mechanism fashioned and run by God and his physical laws. The early telescopes, which all relied on visible light, did little to undercut that image of an ordered system. The Moon revolved around Earth. Earth and other planets rotated on their axes and revolved around the Sun. The stars shone. The nebulae floated freely in space.

Not until the nineteenth century was it evident that visible light is just one band of a broad spectrum of electromagnetic radiation—the band that human beings just happen to see. Infrared was discovered in 1800, ultraviolet in 1801, radio waves in 1888, X rays in 1895, and gamma rays in 1900. Decade by decade in the following century, new kinds of telescopes came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into use, fitted with detectors that could "see" these formerly invisible parts of the electromagnetic spectrum. Now astrophysicists began to unmask the true character of the universe.

Turns out that some celestial bodies give off more light in the invisible bands of the spectrum than in the visible. And the invisible light picked up by the new telescopes showed that mayhem abounds in the cosmos: monstrous gamma-ray bursts, deadly pulsars, matter-crushing gravitational fields, matter-hungry black holes that flay their bloated stellar neighbors, newborn stars igniting within pockets of collapsing gas. And as our ordinary, optical telescopes got bigger and better, more mayhem emerged: galaxies that collide and cannibalize each other, explosions of supermassive stars, chaotic stellar and planetary orbits. Our own cosmic neighborhood—the inner solar system—turned out to be a shooting gallery, full of rogue asteroids and comets that collide with planets from time to time. Occasionally they've even wiped out stupendous masses of Earth's flora and fauna. The evidence all points to the fact that we occupy not a well-mannered clockwork universe, but a destructive, violent, and hostile zoo.

Of course, Earth can be bad for your health too. On land, grizzly bears want to maul you; in the oceans, sharks want to eat you. Snowdrifts can freeze you, deserts dehydrate you, earthquakes bury you, volcanoes incinerate you. Viruses can infect you, parasites suck your vital fluids, cancers take over your body, congenital diseases force an early death. And even if you have the good luck to be healthy, a swarm of locusts could devour your crops, a tsunami could wash away your family, or a hurricane could blow apart your town.

So the universe wants to kill us all. But let's ignore that complication for the moment.

Many, perhaps countless, questions hover at the front lines of science. In some cases, answers have eluded the best minds of our species for decades or even centuries. And in contemporary America, the notion that a higher intelligence is the single answer to all enigmas has been enjoying a resurgence. This present-day version of God of the gaps goes by a fresh name: "intelligent design." The term suggests that some entity, endowed with a mental capacity far greater than the human mind can muster, created or enabled all the things in the physical world that we cannot explain through scientific methods.

An interesting hypothesis.

What comedian designer configured the region between our legs— an entertainment complex built around a sewage system?

But why confine ourselves to things too wondrous or intricate for us to understand, whose existence and attributes we then credit to a superintelligence? Instead, why not tally all those things whose design is so clunky, goofy, impractical, or unworkable that they reflect the absence of intelligence?

Take the human form. We eat, drink, and breathe through the same hole in the head, and so, despite Henry J. Heimlich's eponymous maneuver, choking is the fourth leading cause of "unintentional injury death" in the United States. How about drowning, the fifth leading cause? Water covers almost three-quarters of Earth's surface, yet we are land creatures—submerge your head for just a few minutes, and you die.

Or take our collection of useless body parts. What good is the pinky toenail? How about the appendix, which stops functioning after childhood and thereafter serves only as the source of appendicitis? Useful parts, too, can be problematic. I happen to like my knees, but nobody ever accused them of being well protected from bumps and bangs. These days, people with problem knees can get them surgically replaced. As for our pain-prone spine, it may be a while before someone finds a way to swap that out.

How about the silent killers? High blood pressure, colon cancer, and diabetes each cause tens of thousands of deaths in the U.S. every year, but it's possible not to know you're afflicted until your coroner tells you so. Wouldn't it be nice if we had built-in biogauges to warn us of such dangers well in advance? Even cheap cars, after all, have engine gauges.

And what comedian designer configured the region between our legs—an entertainment complex built around a sewage system?

The eye is often held up as a marvel of biological engineering. To the astrophysicist, though, it's only a so-so detector. A better one would be much more sensitive to dark things in the sky and to all the invisible parts of the spectrum. How much more breathtaking sunsets would be if we could see ultraviolet and infrared. How useful it would be if, at a glance, we could see every source of microwaves in the environment, or know which radio station transmitters were active. How helpful it would be if we could spot police radar detectors at night.

Think how easy it would be to navigate an unfamiliar city if we, like birds, could always tell which way was north because of the magnetite in our heads. Think how much better off we'd be if we had gills as well as lungs, how much more productive if we had six arms instead of two. And if we had eight, we could safely drive a car while simultaneously talking on a cell phone, changing the radio station, applying makeup, sipping a drink, and scratching our left ear.

Stupid design could fuel a movement unto itself. It may not be nature's default, but it's ubiquitous. Yet people seem to enjoy thinking that our bodies, our minds, and even our universe represent pinnacles of form and rea-

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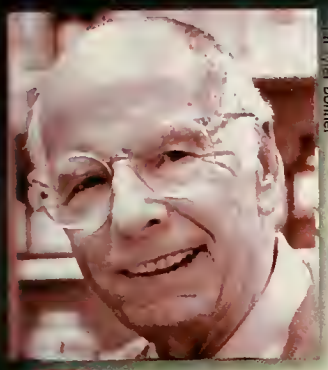
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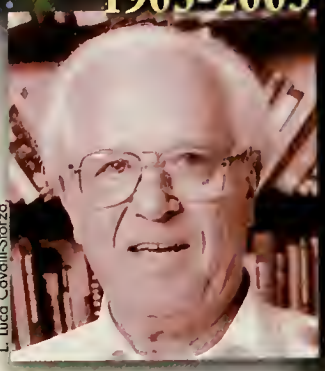
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son. Maybe it's a good antidepressant to think so. But it's not science—not now, not in the past, not ever.

Another practice that isn't science is *embracing* ignorance. Yet it's fundamental to the philosophy of intelligent design: I don't know what this is. I don't know how it works. It's too complicated for me to figure out. It's too complicated for any human being to figure out. So it must be the product of a higher intelligence.

What do you do with that line of reasoning? Do you just cede the solving of problems to someone smarter than you, someone who's not even human? Do you tell students to pursue only questions with easy answers?

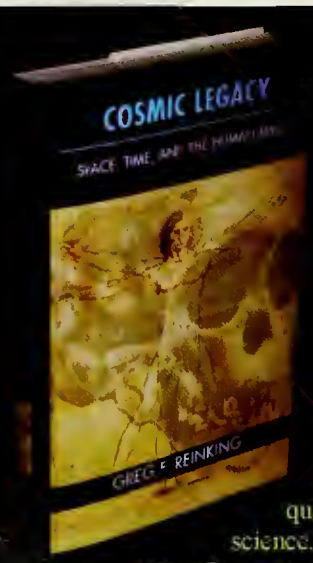
There may be a limit to what the human mind can figure out about our universe. But how presumptuous it would be for me to claim that if I can't solve a problem, neither can any other person who has ever lived or who will ever be born. Suppose Galileo and Laplace had felt that way? Better yet, what if Newton had *not*? He might then have solved Laplace's problem a century earlier, making it possible for Laplace to cross the *next* frontier of ignorance.

Science is a philosophy of discovery. Intelligent design is a philosophy of ignorance. You cannot build a program of discovery on the assumption that nobody is smart enough to figure out the answer to a problem. Once upon a time, people identified the god Neptune as the source of storms at sea. Today we call these storms hurricanes. We know when and where they start. We know what drives them. We know what mitigates their destructive power. And anyone who has studied global warming can tell you what makes them worse. The only people who still call hurricanes "acts of God" are the people who write insurance forms.

To deny or erase the rich, colorful history of scientists and other thinkers who have invoked divinity in their work would be intellectually dishonest. Surely there's an appropriate place for intelligent design to live in the academic landscape. How about the history of religion? How about philosophy or psychology? The one place it doesn't belong is the science classroom.

If you're not swayed by academic arguments, consider the financial consequences. Allow intelligent design into science textbooks, lecture halls, and laboratories, and the cost to the frontier of scientific discovery—the frontier that drives the economies of the future—would be incalculable. I don't want students who could make the next major breakthrough in renewable energy sources or space travel to have been taught that anything they don't understand, and that nobody yet understands, is divinely constructed and therefore beyond their intellectual capacity. The day that happens, Americans will just sit in awe of what we don't understand, while we watch the rest of the world boldly go where no mortal has gone before.

Astrophysicist NEIL DEGRASSE TYSON *is the director of the Hayden Planetarium at the American Museum of Natural History. An anthology of his "Universe" columns will be published in 2006 by W.W. Norton.*



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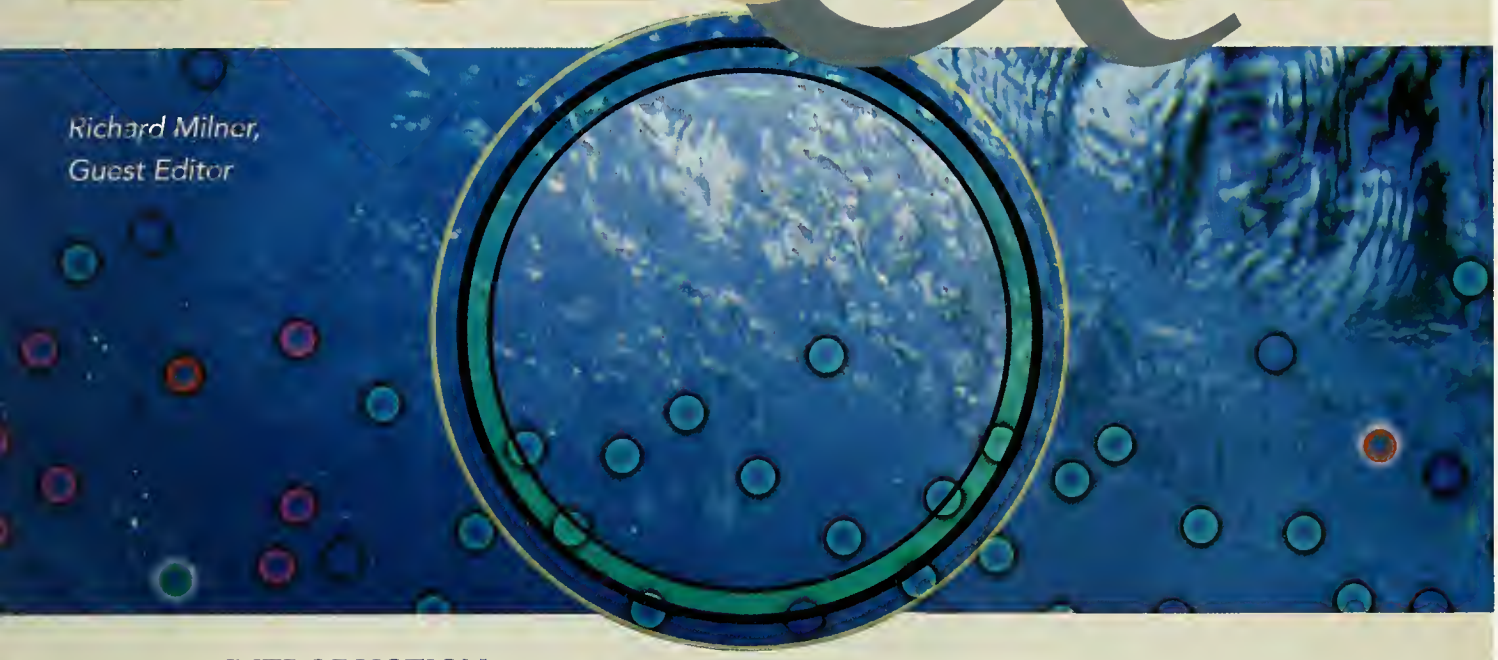
NATURAL HISTORY
NOVEMBER 2005

Darwin & EVOLUTION



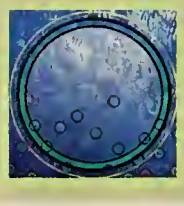
Richard Milner,
Guest Editor

INTRODUCTION

The Illusion of Design

By Richard Dawkins

The world is divided into things that look as though somebody designed them (wings and wagon-wheels, hearts and televisions), and things that just happened through the unintended workings of physics (mountains and rivers, sand dunes, and solar systems). Mount Rushmore belonged firmly in the second category until the sculptor Gutzon Borglum carved it into the first. Charles Darwin moved in the other direction. He discovered a way in which the unaided laws of physics—the laws according to which things "just happen"—could, in the fullness of geologic time, come to mimic deliberate design. The illusion of design is so successful that to this day most Americans (including, significantly, many influential and rich Americans) stubbornly refuse to believe it *is* an illusion. To such people,



if a heart (or an eye or a bacterial flagellum) looks designed, that's proof enough that it is designed.

No wonder Thomas Henry Huxley, "Darwin's bulldog," was moved to chide himself on reading the *Origin of Species:* "How extremely stupid not to have thought of that." And Huxley was the least stupid of men. The breathtaking power and reach of Darwin's idea—extensively documented in the field, as Jonathan Weiner reports [*see "Evolution in Action," page 47*]—is matched by its audacious simplicity. You can write it out in a phrase: nonrandom survival of randomly varying hereditary instructions for building embryos. Yet, given the opportunities afforded by deep time, this simple little algorithm generates prodigies of complexity, elegance, and diversity of apparent design. True design, the kind we see in a knapped flint, a jet plane, or a personal computer, turns out to be a manifestation of an entity—the human brain—that itself was never designed, but is an evolved product of Darwin's mill.

Paradoxically, the extreme simplicity of what the philosopher Daniel C. Dennett called Darwin's dangerous idea may be its greatest barrier to acceptance. People have a hard time believing that so simple a mechanism could deliver such powerful results.

The arguments of creationists, including those creationists who cloak their pretensions under the politically devious phrase "intelligent-design theory," repeatedly return to the same big fallacy. Such-and-such looks designed. Therefore it was designed. To pursue my paradox, there is a sense in which the skepticism that often greets Darwin's idea is a measure of its greatness. Paraphrasing the twentieth-century population geneticist Ronald A. Fisher, natural selection is a mechanism for generating improbability on an enormous scale. *Improbable* is pretty much a synonym for *unbelievable*. Any theory that explains the highly improbable is asking to be disbelieved by those who don't understand it.

Yet the highly improbable does exist in the real world, and it must be explained. Adaptive improbability—complexity—is precisely the problem that any theory of life must solve and that natural selection, uniquely as far as science knows, does solve. In truth, it is intelligent design that is the biggest victim of the argument from improbability. Any entity capable of deliberately designing a living creature, to say nothing of a universe, would have to be hugely complex in its own right.

If, as the maverick astronomer Fred Hoyle mistakenly thought, the spontaneous origin of life is as improbable as a hurricane blowing through a junkyard and having the luck to assemble a Boeing 747, then a divine designer is the ultimate Boeing 747. The designer's spontaneous origin ex nihilo would have to be even more improbable than the most complex of his alleged creations. Unless, of course, he relied on natural selection to do his work for him! And in that case, one might pardonably wonder (though this is not the place to pursue the question), does he need to exist at all?

Many people cannot bear to think that they are cousins of tapeworms, spiders, and bacteria. The unpalatability of a proposition, however, has no bearing on its truth.

The achievement of nonrandom natural selection is to tame chance. By smearing out the luck, breaking down the improbability into a large number of small steps—each one somewhat improbable but not ridiculously so—natural selection ratchets up the improbability. As the generations unfold, ratcheting takes the cumulative improbability up to levels that—in the absence of the ratcheting—would exceed all sensible credence.

Many people don't understand such nonrandom cumulative ratcheting. They think natural selection is a theory of chance, so no wonder they don't believe it! The battle that we biologists face, in our struggle to convince the public and their elected representatives that evolution is a fact, amounts to the battle to convey to them the power of Darwin's ratchet—the blind watchmaker—to propel lineages up the gentle slopes of Mount Improbable.

The misapplied argument from improbability is not the only one deployed by creationists. They are quite fond of gaps, both literal gaps in the fossil record and gaps in their understanding of what Darwinism is all about. In both cases the (lack of) logic in the argument is the same. They allege a gap or deficiency in the Darwinian account. Then, without even inquiring whether intelligent design suffers from the same deficiency, they award victory to the rival "theory" by default. Such reasoning is no way to do science. But science is precisely *not* what

creation "scientists," despite the ambitions of their intelligent-design bullyboys, are doing.

In the case of fossils, as Donald R. Prothero documents [*see "The Fossils Say Yes," page 52*], today's biologists are more fortunate than Darwin was in having access to beautiful series of transitional stages: almost cinematic records of evolutionary changes in action. Not all transitions are so attested, of course—hence the vaunted gaps. Some small animals just don't fossilize; their phyla are known only from modern specimens: their history is one big gap. The equivalent gaps for any creationist or intelligent-design theory would be the absence of a cinematic record of God's every move on the morning that he created, for example, the bacterial flagellar motor. Not only is there no such divine videotape: there is a complete absence of evidence of any kind for intelligent design.

Absence of evidence *for* is not positive evidence *against,* of course. Positive evidence against evolution could easily be found—if it exists. Fisher's contemporary and rival J.B.S. Haldane was asked by a Popperian zealot what would falsify evolution. Haldane quipped, "Fossil rabbits in the Precambrian." No such fossil has ever been found, of course, despite numerous searches for anachronistic species.

There are other barriers to accepting the truth of Darwinism. Many people cannot bear to think that they are cousins not just of chimpanzees and monkeys, but of tapeworms, spiders, and bacteria. The unpalatability of a proposition, however, has no bearing on its truth. I personally find the idea of cousinship to all living species positively agreeable, but neither my warmth toward it, nor the cringing of a creationist, has the slightest bearing on its truth.

The same could be said of political or moral objections to Darwinism. "Tell children they are nothing more than animals and they will behave like animals." I do not for a moment accept that the conclusion follows from the premise. But even if it did, once again, a disagreeable consequence cannot undermine the truth of a premise. Some have said that Hitler founded his political philosophy on Darwinism. This is nonsense: doctrines of racial superiority in no way follow from natural selection, properly understood. Nevertheless, a good case can be made that a society run on Darwinian lines would be a very disagreeable society in which to live. But, yet again, the unpleasantness of a proposition has no bearing on its truth.

Huxley, George C. Williams, and other evolutionists have opposed Darwinism as a political and moral doctrine just as passionately as they have advocated its scientific truth. I count myself in that company. Science needs to understand natural selection as a force in nature, the better to oppose it as a normative force in politics. Darwin himself expressed dismay at the callousness of natural selection: "What a book a Devil's Chaplain might write on the clumsy, wasteful, blundering low & horridly cruel works of nature!"

In spite of the success and admiration that he earned, and despite his large and loving family, Darwin's life was not an especially happy one. Troubled about genetic deterioration in general and the possible effects of inbreeding closer to home, as James Moore documents, and tormented by illness and bereavement, as Richard Milner's interview with the psychiatrist Ralph Colp Jr. shows, Darwin's achievements seem all the more remarkable [*see "Good Breeding," page 45*, and *"Darwin's Shrink," page 42*]. He even found the time to excel as an experimenter, particularly with plants. David Kohn's and Sheila Ann Dean's essays lead me to think that, even without his major theoretical achievements, Darwin would have won lasting recognition as an experimenter, albeit an experimenter with the style of a gentlemanly amateur, which might not find favor with modern journal referees [*see "The Miraculous Season," page 38*, and *"Bee Lines and Worm Burrows," page 40*].

As for his major theoretical achievements, of course, the details of our understanding have moved on since Darwin's time. That was particularly the case during the synthesis of Darwinism with Mendelian digital genetics. And beyond the synthesis, as Douglas J. Futuyma explains and Sean B. Carroll details further for the exciting new field of "evo-devo," Darwinism proves to be a flourishing population of theories, itself undergoing rapid evolutionary change [*see "On Darwin's Shoulders," page 64*, and *"The Origins of Form," page 58*].

In any developing science there are disagreements. But scientists—and here is what separates real scientists from the pseudoscientists of the school of intelligent design—always know what evidence it would take to change their minds. One thing all real scientists agree upon is the fact of evolution itself. It is a fact that we are cousins of gorillas, kangaroos, starfish, and bacteria. Evolution is as much a fact as the heat of the sun. It is not a theory, and for pity's sake, let's stop confusing the philosophically naive by calling it so. Evolution is a fact. □

The Miraculous Season

Tramping in the fields and tinkering in the greenhouse, Darwin created a revolution in botany.

By David Kohn

The spring and summer of 1860 were the first growing seasons after the *Origin of Species* appeared. Darwin anxiously kept tabs on the debate about his revolutionary theory, which raged that summer—notably at the Oxford meeting of the British Association for the Advancement of Science. But he stayed out of the crossfire and spent his time out of doors, observing living plants. He roamed the fields and chalky banks around Down House, his home in Kent, and the acid bogs of Ashdown Forest in Sussex. And, in rapid succession, he made one critical observation after another—first on the common English plants known as primulas, then on native orchids, and then on insect-eating sundews. In six weeks he changed the world's understanding of plants.

Every year the fields and banks near Down House are dotted with cowslips and primroses, all members of the genus *Primula.* While still at work on *Origin* in the spring of 1859, Darwin had transplanted various primulas to his garden, continuing the work of his botanical mentor at Cambridge, John S. Henslow, on the taxonomy of the genus. By early May 1860 the offspring of his transplants were in bloom, and Darwin observed something that captured his interest. Each species produced two kinds of flowers: some plants had flowers with long styles (the slender extension of the pistils, or female parts) and short stamens (topped with pollen-bearing anthers, the male parts); others had flowers with short styles and long stamens. At once, he sent his children out into the fields to collect primulas by the bunch. To his amazement, the two kinds of plants occurred in a one-to-one ratio.

Darwin already thought that cross-fertilization was the underlying function of flowers, and so his first explanation of this ratio was that perhaps the plants were intermediates in the evolution of separate male and female forms. One can imagine him thinking that the short-style flowers might be almost pure males. He tested this idea experimentally, and found to his further amazement that plants he thought of as "male" produced just as many seeds as the "females." Indeed, like most flowering plants, both forms were hermaphrodites. Then he grasped the key point: only crosses between the two different forms of flowers produced the full complement of healthy seeds—thus short-stamen plants must pollinate short styles, and tall stamens must pollinate tall styles, to get full fertility.

To Darwin the point of the system was evident: it was an elaborate way to avoid self-fertilization. The fact that fertility was diminished in crosses between two plants of the same form implied that fertility would also be diminished in any offspring resulting from self-fertilization. Thus, he concluded, the system—which he called heterostyly—promotes outcrossing.

Darwin reasoned that perpetual self-fertilization would eventually eliminate the range of hereditary variation available to the plant and would therefore close off its further evolution. Thus his newly discovered botanical breeding system showed flowering plants in a revolutionary light: as potentially vulnerable hermaphrodites that have evolved complex adaptations against severe inbreeding.

It is worth noting how important Darwin's analysis was to the understanding of flowering plants. Until the mid-nineteenth century, botanists commonly held that the purpose of flowers was to guarantee seed production. Many respected botanists of the day resisted mounting evidence that insects act as cross-pollinators. Instead, they clung to the idea that insect pollinations were accidental, and that flowers were simply beautiful gifts of a divine beneficence [*see "Mystery of the Red Rose," by Richard Milner, May 1999*]. The insight was a coup for natural selection. Darwin had long grasped that for hermaphroditic plants to have evolved, they would have needed powerful outbreeding systems. Even as the mighty gentlemen of British science prepared to gather in Oxford, Darwin was well on his way to deploying thousands of flowering plant species in support of the evolutionary case.

There was hardly a time when orchids did not figure in Darwin's scientific work. But the defining episode came within days of his *Primula* discoveries. Between May 18 and June 3, 1860, Darwin first probed the flowers of *Orchis mascula* (early

purple orchid) and *O. pyramidalis* (pyramidal orchid) with the point of a pencil, to simulate the proboscis of a moth.

Those flowers are effectively spring-loaded, and Darwin found that the slightest touch released the embedded pollen mass, which would then become attached the pencil by a sticky gland. Then, astonishingly, as the adhesive secretion dried, the pollen mass would bend over. Darwin realized that when a moth with pollen masses stuck on its proboscis visited the next flower, the bent-over pollen mass would be aligned for perfect delivery onto the new flower's stigma. These were exciting and original observations, guided as before by Darwin's firm belief that the structure of flowers had evolved to ensure cross-pollination and that insects are the necessary transport agents for the pollen.

Perhaps the best-known tale of Darwin and orchids comes from his study of the Madagascan comet orchid, whose long nectary led him to correctly predict the existence of a moth pollinator with an eleven-inch proboscis [*see "The Flower and the Fly," by Laura A. Sessions and Steven D. Johnson, March 2005*]. Far more significant, however, is the scope of what he accomplished in a few weeks in his native England. His investigation of the comparative anatomy of orchid fertilization became his first extended case study of adaptive evolution. Meanwhile, the Oxford meeting had begun, and Bishop Samuel Wilberforce and Thomas Henry Huxley were making monkeys of themselves exchanging sarcastic jibes about the merits of Darwin's theory.

One British orchid Darwin could not find near Down House was *Malaxis paludosa*, bog adder's-mouth. So within weeks of beginning his work with orchids, he visited a relative who lived at the edge of Ashdown Forest. There, while hunting for the rare bog orchid, he stumbled on the minuscule, insectivorous sundew plant, *Drosera rotundifolia*. To the sundew, insects are prey rather than pollinators. And so Darwin was off and running for the third time that summer, with experiments to peer into the workings of insectivorous plants and to sort out the tangled web of plant-animal adaptations. In the next few weeks he first watched the plants kill flies, gnats, and spiders. He then tested them with raw meat. He also tried to irritate them with a camel-hair brush, bits of quill, and dry cinder. Have they "knowledge," as he put it, of the difference between organic and inorganic stimuli? By the time he returned to Down House, Darwin had even anaesthetized his plants with chloroform. Darwin's wife, Emma, wrote a friend that "he is treating *Drosera* just like a living creature, and I suppose he hopes to end in proving it to be an animal."

The three botanical discoveries of the summer of 1860 ultimately turned the last two decades of Darwin's life into an unending series of experiments. Three books are immediately traceable to that summer: *On the Various Contrivances by which British and Foreign Orchids Are Fertilised by Insects* (1862), *Insectivorous Plants* (1875), and *The Different Forms of Flowers on Plants of the Same Species* (1877).

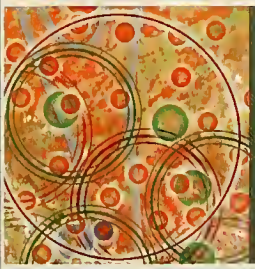
Some biographers have emphasized that Darwin's botany sprang from his wish to dodge the public controversies that raged the moment he launched his theory, wars that he had anticipated and feared. But that assessment ignores an important historical fact. The best, most consistent, and

most enduring web of evidence that Darwin ever developed in defense of his theory was botanical.

Darwin's botany elucidated two grand themes: the adaptive function of flowers and the nature of sensitivity in plants. He pursued both themes to advance the theory of evolution by natural selection. The strength of his evidence not only helped gain early acceptance of his theory but also attracted an international network of botanical co-workers, who around the turn of the century carried on his evolutionary vision. That was a time—before the mechanism of Mendelian inheritance was appreciated—that the theory of natural selection was neglected or challenged.

So what Darwin was doing as the churchmen and professors debated was not really creative evasion. He was switching gears from theorist to full-blown experimentalist and raising bulwarks of fact against the attackers of his theory. His evolutionary explanations for the role of flowers and more broadly of sex, for tactile and chemical sensitivity, for the core relations of plant-insect ecology, and for "engineering" details that laid the foundations of evolutionary physiology—all came out of the concerted research program that took shape in 1860.

Darwin's two botanical themes—sex and sensitivity—immediately became part of the core of evolutionary biology, and remain unassailed to this day. Many of his other concepts got mixed receptions: Pangenesis, Darwin's theory of how favorable traits might be acquired and inherited, was rejected. And the principle of divergence, his long-forgotten effort to explain how and why, through natural selection, one species living in a single range would split into separate descendant species, was not to become part of the evolutionary synthesis—the refined formulation developed among evolutionary biologists in the mid-twentieth century. Darwin's ideas on sexual selection, human origins in Africa, and even natural selection itself were accepted only after decades of debate. But his rewriting of pollination biology and plant physiology has endured, the glorious fruit of a miraculous summer. □



Bee Lines and Worm Burrows

Growing up as Darwin's little helpers

By Sheila Ann Dean

Charles and Emma Darwin moved from London to Down, Kent, in 1842, when their first two children, William and Annie, were still small. As Emma gave birth to more children, their father grew comfortably ensconced in the country house that he would rarely leave. His study, the sitting room, and greenhouses became a gentleman's laboratory; his gardens and the surrounding meadows and woodlands became field stations for his observations and experiments. The children's involvement in science began in infancy, as experimental subjects, while their affectionate, attentive, but intensely curious father scrutinized their development.

William ("Doddy") was born in 1839. The father's notes on the boy reflect Darwin's keen interest in the origin of expressions and the extent to which they were inherited. He noted William's smiles, frowns, and gestures. He knew it was hard to prove that children instinctively recognize any expression but was convinced that William "understood a smile and received pleasure from seeing one, answering it by another, at much too early an age to have learnt anything by experience." When his son was a year old, Darwin noted that, to "his word for food . . . he gives the *most strongly marked* interrogatory sound at end . . . analogous to cry for food of nestling-birds, which certainly is instinctive & peculiar to that time of life." Darwin later used his notes for his 1872 book, *The Expression of the Emotions in Man and Animals,* and they formed the basis of "A Biographical Sketch of an Infant," an article published in 1877 in the journal *Mind.*

His children began discovering natural history themselves at an early age. In 1855 at age five, Darwin's fourth son, Leonard, ran to a flower exclaiming, "I've a fact to do." By then his father had launched into his botanical studies, with a particular interest in how insects cross-pollinate plants [*see "The Miraculous Season," by David Kohn, page 38*]. On at least one occasion he stationed several children at plants he knew to be pollinated by bumblebees. As a bee visited a flower, the child dusted the insect with flour and shouted where it was headed next. Mapping the flight of a bumblebee thus became a Darwin family project.

Darwin's longstanding enthusiasm for beetles and

other insects apparently inspired several of his sons. As a teenager, Darwin's second son, George, clambered over the so-called Orchis Bank on summer nights, observing the pollination of *Gymnadenia conopsea,* the fragrant orchid, among others. Darwin, who described George as "an entomologist and careful observer," cited his work in the second edition of his 1862 book, *On the Various Contrivances by which British and Foreign Orchids Are Fertilised by Insects, and on the Good Effects of Intercrossing.* George, he recorded, caught four different moth species with "pollinia attached to their proboscides."

In the 1860s, William—once the subject of his father's observations on infant expression—assisted in Darwin's studies of dimorphic plants, species that have two reproductive forms. By then a young banker in Southampton, William happily labored on weekends collecting dimorphic *Primulas*, *Pulmonaria* (lungworts), and *Lythrum* (purple loosestrife), meticulously sketching and measuring anthers, pollen grains, stamens, and stigmas for his father. Their correspondence is crowded with diagrams and debates about the arcana of their passion.

Not always restricted to science, the letters from Down included household news—Emma's comments on her husband's health, how the heat had shortened the bloom of the azaleas. William's letters thanked his mother for the corn plaster just sent, or noted the dates of his next visit home.

Henrietta, Darwin's third daughter, also helped her father, though the historical evidence is harder to ferret out. Like most Victorian daughters, she was not sent away to school or to university as her brothers were, and she lived at home until she married. Nevertheless, botanical notes of Darwin's, written in her hand, make it clear that she was often at her father's side in the greenhouses and gardens. She probably helped by tying thread to stems to mark plants, or by examining flower parts with a magnifying glass. When Darwin received some new plants for the hothouse, he wrote to a friend that he and Henrietta "go & gloat over them." He added: "We privately confessed to each other, that if they were not our own, perhaps we shd. not see such transcendent beauty in each leaf."

Henrietta's involvement gave her a botanical background that would later be put to good use, in proofreading and editing many of her father's later books. Darwin wrote her in France that her criticisms on the manuscript for his 1868 book, *The Variation of Animals and Plants under Domestication,* were "excellent, excellent, excellent." Henrietta's work at Down is one more example of what is now a growing body of evidence for the participation of women in Victorian science. Most of the women were the relatives of men of science, and though many of their contributions were quiet, they were often significant.

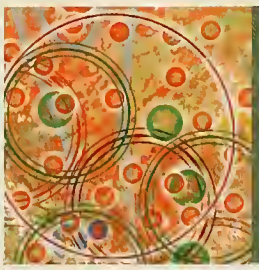
Darwin made perhaps his most unusual requests for help during his study of worms. He enlisted his daughters and other female relatives to follow the creatures and measure the angles of their burrows. His helpers poked knitting needles into the worm holes and duly noted the results. Darwin wanted the information for the book, published in 1881, that

would be his last: *The Formation of Vegetable Mould, through the Action of Worms with Observations on their Habits.* One of the best-known findings that Darwin reported in the book was that earthworms had played an important role in undermining and burying Roman ruins, by transporting soil to the surface. Three of Darwin's sons helped establish that result. And a fourth, Darwin's third son, Francis, famously played his bassoon over worms to test whether they could hear. (They couldn't.)

Darwin clearly appreciated his children's help, but his paternal delight may have far exceeded his appreciation. How wonderful it was for him to discover his children's growing awareness of what he was ultimately up to. In 1862 Darwin glowingly wrote to the American botanist Asa Gray about his fifth son, Horace, then eleven years old:

> Horace said to me, "there are a terrible number of adders here; but if everyone killed as many as they could, they would sting less."— I answered "of course they would be fewer" Horace replied "Of course, but I did not mean that; what I meant was, that the more timid adders which run away & do not sting would be saved, & after a time none of the adders would sting."

Darwin proudly added: "Natural selection!!" □



Darwin's Shrink

A noted Darwin historian probes the naturalist's inner life.

By Richard Milner

Psychiatrist Ralph Colp Jr.'s favorite patient has been buried in Westminster Abbey since 1882. Nevertheless, Colp has come to know him intimately through unpublished letters, his medical diary, and written reminiscences of his family and friends in British and American archives. The patient is Charles Darwin, about whom Colp has written many articles and the classic, 1977 book, To Be an Invalid: The Illness of Charles Darwin, *which he is currently revising.*

After practicing surgery for five years, Colp switched to psychiatry and became a Diplomate of the American Board of Psychiatry and Neurology (Psychiatry) in 1965. He served as attending psychiatrist at Columbia University Health Services until 1993, and is now a senior associate in the Program of Human Sexuality and Sex Therapy at the New York University Medical Center and a member of the Psychohistory Forum. But it is his labor of love that has earned him a reputation as the dean of Darwin historians. In a series of conversations, Natural History *questioned Colp, now 81, about Darwin's personality, family life, politics, and illness.*

NATURAL HISTORY: When did you first become interested in Charles Darwin?

RALPH COLP JR.: My father was a surgeon, and in his office were framed portraits of Darwin, Freud, Huxley, Lister, and Pasteur. As a child, I thought they were heroes of science, much nobler than my father and his colleagues who practiced medicine as a business.

When I was in high school, in the 1940s, my biology teacher said, "Nobody believes in Darwinism any more," yet she kept mentioning him. I saw that he was exerting a force, still stirring up controversies sixty years after his death. But my interest from the first, staring at Darwin's portrait when I was a boy, was, "What was he like as a man?" I really started taking him on seriously in 1959, when I was thirty-five, and there were all the scientific celebrations and press reports about the centenary of the *Origin of Species.*

NH: How can one analyze the mental state of a person who died long ago?

COLP: Darwin's life is extraordinarily well documented by letters, diaries, notebooks, and his own record of his health. His handwriting is often very difficult to decipher, however, and even when you do decipher it, you might find some fragment incomprehensible. It can call for a bit of scholarly sleuthing.

For instance, in an 1858 letter to his wife, Emma, Darwin complains that he had been to Farnham in Surrey, and that "the Review and the confounded Queen" made him feel ill. What could that mean? Perhaps a nasty article about the Queen had appeared in the popular magazine *Quarterly Review*? I searched it in vain. But when I checked newspapers for the Queen's whereabouts on that date, I found that she was near Farnham reviewing some troops. Now it was clear: this man who I knew loved military parades was upset by the sloppy drill de-

scribed in the article, which mentioned that the soldiers kicked up clouds of dust. So he came alive for me there. Multiply that by hundreds of instances of figuring out the meaning of fragments.

NH: How well do you feel you know him?

COLP: Probably much better than I know some of my living friends and patients. I'm interested in physical details as well as his emotional and inner life. Even the way he walked, or worked, or the quality of his laugh—it was thin, musical, and hollow sounding, like a peal. He and Thomas Huxley liked to sit and joke and laugh for hours.

Darwin lived an exemplary life as an English country gentleman, the affectionate father to a brood of seven children. Sometimes he sat on the local magistrate's bench as a Justice of the Peace, "to help keep order in the neighborhood." He was always kind and considerate to his servants and gardeners, and taught his children to always address them with "please" and "thank you."

NH: What are your views on his illness?

COLP: When I first began in 1959, I noticed that the many biographies of him had little to say about the causes and nature of the illness that dominated his life. In *To Be an Invalid,* I published the first comprehensive account of his illness. I showed that as a youth he suffered brief psychosomatic symptoms from transient mental stresses, and as an adult he suffered protracted psychosomatic illness—altered sensations, cardiac palpitations, headaches, and trembling—mainly from working on his controversial theory of evolution. He had told a friend that to abandon Church teachings on the immutability of species was "like confessing a murder." He delayed writing the *Origin of Species* for more than twenty years, until a younger naturalist, Alfred Russel Wallace, forced his hand. His endless agonizing, guilt, and self-flagellation over writing and publishing could be described as obsessive. When his theory was accepted and he stopped working on it, his health improved.

Darwin was always a sensitive individual, but after the *Beagle* voyage he became even more so, and two years afterward suffered a debilitating illness. His condition points to an organic disease. But Darwin's own doctors were baffled. Not until 1959 did Saul Adler, an Israeli parasitologist, suggest that Darwin's illness was Chagas' disease. During Darwin's lifetime the disease was not yet known to medicine, so it is no wonder it was never diagnosed.

In 1835 Darwin had recorded in his diary that he was bitten by the "*Benchuca* [*vinchuca*] bug . . . called the great black bug of the Pampas," a vector of the parasitic trypanosome that causes Chagas' disease [*see "In the Heat of the Night," by Graciela Flores, July-August 2005*]. Darwin appears to have had the arrested form of the disease, which can appear years after the bite and causes weakness, nausea, and flatulence for many years.

NH: How did the illness affect his daily life?

COLP: He could only work for two or three hours a day, and therefore followed a regimen of alternat-

ing work and rest. Yet his dogged determination carried him through thousands of experiments, seventeen books, and a hundred scientific papers. His wife, Emma, would regulate any visitors and strictly limit the time they were with him; he rarely left home and described himself as a "semi-invalid." But he often used his illness as a convenient excuse to avoid unwanted visitors and dinner parties.

NH: Can we discuss the death of his daughter Annie, on which you've written the article "Charles Darwin's 'insufferable grief'" [*Free Associations* 9:7–44 (1987)]?

COLP: He had an enormous capacity for love, but was inhibited in expressing it. His sisters, who raised him, never talked about his mother, who died when he was eight years old. He learned to hold back his emotions, but when Annie died at the age of ten in April 1851 from "fever" (which some now believe was tuberculosis), he was inconsolable. It was the first time anyone had seen him cry. His sister-in-law was present and wept with him.

Darwin expressed his feelings in a moving tribute to Annie, containing precise observations of her, along with his outpourings of affection. Here are some passages:

> Her dear face now rises before me, as she used sometimes to come running down stairs with a stolen pinch of snuff for me, her whole form radiant with the pleasure of giving pleasure. . . . She would at almost anytime spend half-an-hour in arranging my hair, "making it," as she called it, "beautiful," or in smoothing, the poor dear darling, my collar or cuffs, in short in fondling me. She liked being kissed; indeed every expression in her countenance beamed with affection & kindness, & all her habits were influenced by her loving disposition. . . .
>
> All her movements were vigorous, active, & unusually graceful: when going round the sand-walk with me, although I walked fast, yet she often used to go before pirouetting in the most elegant way, her dear face bright all the time, with the sweetest smiles. . . . [In the last days of her illness,] when so exhausted that she could hardly speak, she praised everything that was given her, & said some tea "was beautifully good." When I gave her some water, she said "I quite thank you"; & these, I believe were the last precious words ever addressed by her dear lips to me. . . . We have lost the joy of the Household, and the solace of our old age.

Annie's death seemed to him so unjust that it precipitated his loss of belief in God.

NH: Did he have strong feelings on social issues?

COLP: Yes, he grew up in an anti-slavery household. The Wedgwood-Darwin family had a long tradition of Abolitionist support. A famous Wedgwood ceramic plaque shows a slave in chains with the slogan, "Am I not a man and a brother?"

In Brazil he witnessed slavery firsthand, and never forgot the screams of a tortured slave coming from a house in Pernambuco. Watching or hearing people in pain made him physically ill. That was why he could not become a surgeon himself, as his father had wished. He fled from the operating theater at Edinburgh when he could not bear the screams of a strapped-down child in surgery—and never returned to pursue his medical career. He was against slavery not only on political and humane grounds, but also because it made him literally sick to his stomach.

NH: And yet he abandoned the cause during the American Civil War?

COLP: In 1861 Union troops boarded the English mail steamer RMS *Trent* and seized two Confederate officials who were bound for London to seek support for the Rebels. The English declared that to be an act of war unless the pair was freed.

Darwin began to fear that the provocation by the North might lead to war between England and America. So he stopped supporting the Union cause, and opined that the North should learn to co-exist peacefully with the slave-owning South. Here was the strongest political principle that he had, and he compromised it out of petty patriotism. What the hell was wrong with him? He knew better than that.

NH: Has your intimate knowledge of Darwin influenced your own life?

COLP: As a young man, I realized that there were certain similarities. Like Darwin, I grew up in the shadow of a prominent physician for a father, and was expected to follow in his footsteps to become a surgeon. Like Darwin, I rebelled against following the path that had been set out for me. Although I did practice surgery for several years, I was more interested in the mind and the emotions and became a psychiatrist.

I have grown to imitate Darwin in many ways. My daily habits of early rising and then doing important writing first thing, for instance, and how I organize my day around strictly timed alternating periods of work and relaxation, of annotating and abstracting the books that I read, and of writing my first drafts on the backs of used sheets of paper—all of these habits I picked up from Darwin.

He kept a diary on the early emotional expressions of his children, and I did the same when my daughters were infants. I try to be caring and helpful to my friends, as he did. When his friend Sir Joseph Hooker's young son fell ill, Darwin drew on his own agonizing deathwatch of Annie to comfort him: "Much love much trial, but what an utter desert is life without love." □

Good Breeding

Darwin doubted his own family's "fitness."

By James Moore

Brought up in a provincial market town, Charles Darwin lived for forty years in rural Kent, where he raised a large family. The English countryside was his natural habitat, a world of gentleman farmers devoted to breeding livestock, flowers, fruit—and people. His paternal grandfather, Erasmus Darwin, was a noted horticulturalist, and his maternal grandfather, Josiah Wedgwood I, who raised sheep, improved the flocks with hundreds of Merinos. "It is a beautiful part of my theory," Charles jotted, when developing his ideas on evolution, "that domesticated races . . . are made by precisely [the] same means as species." Breeders decided which animals mate and which offspring survive—this was "artificial selection." Nature, in Darwin's view, did the same thing through the struggle for existence: he called it "natural selection."

Ironically, some of the problems caused by inbreeding, which Darwin had heard about from farmers, threatened to play out in his own family. In 1839, as he turned thirty, did Charles select well in choosing a mate? His betrothed, Emma Wedgwood, was his first cousin. The Darwin and Wedgwood families had intermarried for some time (I call them the Darwoods, for short). Charles's grandfather Josiah had eight children with his third cousin Sarah. Their eldest daughter, Susannah, married Robert Darwin, a noted physician; Charles was the fifth of Robert and Susannah's six children. Josiah and Sarah's second-eldest son, Josiah II, fathered nine children, four of whom, Emma Wedgwood Darwin among them, married first cousins.

From our vantage point long after Darwin's death, the results of this unintended experiment in close-cousin breeding are striking. Twenty-six children were born from these first-cousin marriages, yet nineteen of the offspring did not reproduce: five died prematurely, five were unmarried and considered somehow deficient, and nine married without issue. Indeed, among the sixty-two aunts, uncles, and cousins in the four generations founded by Josiah I and Sarah Wedgwood, thirty-eight remained childless. Just as Britain's population was booming, the fertility of Darwins and Wedgwoods seemed to be falling.

When Charles's mixed Darwood blood was added to Emma's "pure" Wedgwood, how would their children turn out? Darwin observed them tenderly, but with a breeder's eye, starting with Willy, "my lit-

tle animalcule of a son," and his first daughter, Annie. A third child, Mary, died shortly after her birth, but other healthy babies followed—Henrietta, George, Elizabeth, Francis, and Leonard. Then the eldest girl, Annie, fell ill in 1850. She died a year later, soon after her tenth birthday. Another son, Horace, was born in 1851.

Darwin was devastated by Annie's death, fearing she had inherited the "wretched" illness that had plagued him since the *Beagle* voyage. (Historians now think Annie died of tuberculosis, while Darwin was infected by a blood parasite he acquired in the tropics.) As the other children reached the age at which Annie had become sick, he watched them anxiously. "My dread is hereditary ill-health," he confided in a letter. "Even death is better for them."

He found what he feared. Elizabeth "shivers & makes . . . extraordinary grimaces"; at age ten she developed a weak, irregular pulse. Henrietta had similar symptoms at age thirteen and took to her bed for years. George's irregular pulse at age eight pointed to "some deep flaw in his constitution," his father assumed, and he spotted the same symptom at the same age in Leonard.

As the children failed—or appeared to fail—one after another, Darwin began experimenting with pigeons. He bought fancy varieties and worked out their family tree; he observed the chicks to determine the age at which slight "differences appear" that breeders could select or nature could exploit. Those variations, as Darwin wrote in the *Origin of Species,* usually arose "at a corresponding age in the offspring" and parent, but he knew of cases in which flaws appeared "at an earlier age in the child." The evidence for the latter lived at home. His own condition had set in about age thirty, the children's as adolescence approached, seemingly like clockwork.

In 1856 the Darwins' tenth and final child arrived without its "full share of intelligence." Baby Charles never began to talk; he shivered and grimaced, and died within two years. But the evidence that the family was blighted already seemed abundantly clear. In 1862, when Horace broke down at age eleven, "with shuddering & gasping & hysterical sobbing," his father felt he knew the cause: it was "a serious form of inheritance from my poor constitution." Now, to clinch the diagnosis, all he needed was quantitative proof that inbreeding was bad—evidence from more than his own ten offspring.

Darwin turned to breeding plants in his garden and greenhouses. His experiments proved to him what he had always feared about his family: the offspring of close or self-fertilizing "illegitimate unions" were weak and stunted compared with the offspring of "legitimate unions" between unrelated parents.

In the 1860s Darwin's own half-first cousin Francis Galton, who compiled Darwin's plant data, proposed to improve Britain's human "stock" through selection in marriage. Darwin thought the scheme "Utopian," but he knew the importance of statistics about fertility. A national census was to be conducted in Britain in 1871, and Darwin asked Parliament to insert a simple, relevant question, asking whether the respondent was married to a first cousin. That information, together with the number of surviving children listed in the census, would be telling. If cousin couples could be shown to produce fewer surviving children than unrelated spouses, there would be a scientific basis for a social policy banning close-cousin unions.

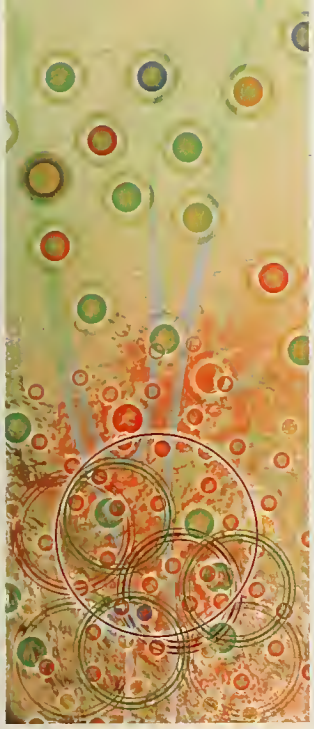
In Parliament a hot debate erupted. Members declared the question "inquisitorial" and "the grossest cruelty ever thought of." Imagine children being "anatomised by science," like "plants and animals"! First cousins might be banned from marrying, causing "mental torture" to couples. Darwin's question was thrown out by a margin of two to one.

The snub hurt. In his 1871 book, *The Descent of Man,* Darwin berated the "ignorant members of our legislature [for] rejecting with scorn a plan for ascertaining by an easy method whether or not consanguineous marriages are injurious to man."

Darwin turned to his son George—now a Cambridge mathematician, but still sickly, despondent, and expecting to die. George perked up at the prospect of compiling statistics on cousin marriage, and collaborated on the project with Charles's cousin Francis Galton.

In 1883, soon after Darwin's death, Galton was the first to dub the quest for good breeding "eugenics," and in 1907 helped to found the Eugenics Education Society. The Darwin sons joined, and Leonard became president in time to host the First International Congress of Eugenics in London in 1912.

Still childless himself as he pressed for the eugenic improvement of Britain, Leonard went on to mentor a "son" of his own, the brilliant young population geneticist Ronald A. Fisher. In 1930, Fisher became an architect of the so-called synthetic theory of evolution with his classic, *The Genetical Theory of Natural Selection* [*see "On Darwin's Shoulders" by Douglas J. Futuyma, page 64*]. Fisher dedicated the book to Leonard, whose eugenic commitments he shared, both of them knowing—as Leonard well recalled—that "Darwin was just as anxious as his cousin [Galton] to see practical steps taken to promote the gradual improvement of our race through the agency of natural inheritance." □



DARWINISM TODAY

Evolution in Action

Finches, monkeyflowers, sockeye salmon, and bacteria are changing before our eyes.

By Jonathan Weiner

Charles Darwin's wife, Emma, was terrified that they would be separated for eternity, because she would go to heaven and he would not. Emma confessed her fears in a letter that Charles kept and treasured, with his reply to her scribbled in the margin: "When I am dead, know that many times, I have kissed and cryed over this."

Close as they were, the two could hardly bear to talk about Darwin's view of life. And today, those of us who live in the United States, by many measures the world's leading scientific nation, find ourselves in a house divided. Half of us accept Darwin's theory, half of us reject it, and many people are convinced that Darwin burns in hell. I find that old debate particularly strange, because I've spent some of the best years of my life as a science writer peering over the shoulders of biologists who actually watch Darwin's process in action. What they can see casts the whole debate in a new light—or it should.

Darwin himself never tried to watch evolution happen. "It may metaphorically be said," he wrote in the *Origin of Species,*

> that natural selection is daily and hourly scrutinising, throughout the world, the slightest variations; rejecting those that are bad, preserving and adding up all that are good; silently and insensibly working, whenever and wherever opportunity offers. . . . We see nothing of these slow changes in progress, until the hand of time has marked the lapse of ages.

Darwin was a modest man who thought of himself as a plodder (one of his favorite mottoes was, "It's dogged as does it"). He thought evolution plodded too. If so, it would be more boring to watch evolution than to watch drying paint. As a result, for several generations after Darwin's death, almost nobody tried. For most of the twentieth century the only well-known example of evolution in action was the case of peppered moths in industrial England. The moth had its picture in all the textbooks, as a kind of special case.

Then, in 1973, a married pair of evolutionary biologists, Peter and Rosemary Grant, now at Princeton University, began a study of Darwin's process in Darwin's islands, the Galápagos, watching Darwin's finches. At first, they assumed that they would have to infer the history of evolution in the islands from the distribution of the various finch species, varieties, and populations across the archipelago. That is pretty much what Darwin had done, in broad strokes, after the *Beagle*'s five-week survey of the islands in 1835. But the Grants soon discovered that at their main study site, a tiny desert island called Daphne Major, near the center of the archipelago, the finches were evolving rapidly. Conditions on the island swung wildly back and forth from wet years to dry years, and finches on Daphne adapted to each swing, from generation to generation. With the help of a series of graduate students, the Grants began to spend a good part of every year on Daphne, watching evolution in action as it shaped and reshaped the finches' beaks.

At the same time, a few biologists began making similar discoveries elsewhere in the world. One of them was John A. Endler, an evolutionary biologist at the University of California, Santa Barbara, who studied Trinidadian guppies. In 1986 Endler published a little book called *Natural Selection in the Wild,* in which he collected and reviewed all of the studies of evolution in action that had been published to that date. Dozens of new field projects were in

Galápagos finches have been important to evolutionary field studies ever since Charles Darwin belatedly recognized the meaning of their diversity and distribution in the islands. In recent years, biologists observing many generations of the birds have demonstrated that the process of natural selection can be seen in action—in real time and in extraordinary detail. The beaks of Galápagos finches are adapted to their various diets. In the photographs a cactus ground finch, Geospiza scandens, *left, feeds on a cactus blossom with its slender beak; a medium ground finch,* Geospiza fortis, *middle, feeds on seeds of the coral tree* (Erythrina); *and a small ground finch,* Geospiza fuliginosa, *right, rests on a small branch. All three share a common seed-eating ancestor from South America.*

progress. Biologists finally began to realize that Darwin had been too modest. Evolution by natural selection can happen rapidly enough to watch.

Now the field is exploding. More than 250 people around the world are observing and documenting evolution, not only in finches and guppies, but also in aphids, flies, grayling, monkeyflowers, salmon, and sticklebacks. Some workers are even documenting pairs of species—symbiotic insects and plants—that have recently found each other, and observing the pairs as they drift off into their own world together like lovers in a novel by D.H. Lawrence.

The Grants' own study gets more sophisticated every year. A few years ago, a group of molecular biologists working with the Grants nailed down a gene that plays a key role in shaping the beaks of the finches. The gene codes for a signaling molecule called bone morphogenic protein 4 (BMP4). Finches with bigger beaks tend to have more BMP4, and finches with smaller beaks have less. In the laboratory, the biologists demonstrated that they could sculpt the beaks themselves by adding or subtracting BMP4. The same gene that shapes the beak of the finch in the egg also shapes the human face in the womb.

Some of the most dramatic stories of evolution in action result from the pressures that human beings are imposing on the planet. As Stephen Palumbi, an evolutionary biologist at Stanford University, points out, we are changing the course of evolution for virtually every living species everywhere, with consequences that are sometimes the opposite of what we might have predicted, or desired.

Take trophy hunting. Wild populations of bighorn mountain sheep are carefully managed in North America for hunters who want a chance to shoot a ram with a trophy set of horns. Hunting permits can cost well into the six figures. On Ram Mountain, in Alberta, Canada, hunters have shot the biggest of the bighorn rams for more than thirty years. And the result? Evolution has made the hunters' quarry scarce. The runts have had a better chance than the giants of passing on their genes. So on Ram Mountain the rams have gotten smaller, and their horns are proportionately smaller yet.

Or take fishing, which is economically much more consequential. The populations of Atlantic cod that swam for centuries off the coasts of Labrador and Newfoundland began a terrible crash in the late 1980s. In the years leading up to the crash, the cod had been evolving much like the sheep on Ram Mountain. Fish that matured relatively fast and reproduced relatively young had the better chance of passing on their genes; so did the fish that stayed small. So even before the popula-

tion crashed, the average cod had been shrinking.

We often seem to lose out wherever we fight hardest to control nature. Antibiotics drive the evolution of drug-resistant bacteria at a frightening pace. Sulfonamides were introduced in the 1930s, and resistance to them was first observed a decade later. Penicillin was deployed in 1943, and the first penicillin resistance was observed in 1946. In the same way, pesticides and herbicides create resistant bugs and weeds.

Palumbi estimates that the annual bill for such unintended human-induced evolution runs to more than $100 billion in the U.S. alone. Worldwide, the pressure of global warming, fragmented habitats, heightened levels of carbon dioxide, acid rain, and the other myriad perturbations people impose on the chemistry and climate of the planet—all change the terms of the struggle for existence in the air, in the water, and on land. Biologists have begun to worry about those perturbations, but global change may be racing ahead of them.

To me, the most interesting news in the global evolution watch concerns what Darwin called "that mystery of mysteries, the origin of species."

The process whereby a population acquires small, inherited changes through natural selection is known as microevolution. Finches get bigger, fish gets smaller, but a finch is still a finch and a fish is still a fish. For people who reject Darwin's theory, that's the end of the story: no matter how many small, inherited changes accumulate, they believe, natural selection can never make a new kind of living thing. The kinds, the species, are eternal.

Darwin argued otherwise. He thought that many small changes could cause two lines of life to diverge. Whenever animals and plants find their way to a new home, for instance, they suffer, like émigrés in new countries. Some individuals fail, others adapt and prosper. As the more successful individuals reproduce, Darwin maintained, the new population begins to differ from the ancestral one. If the two populations diverge widely enough, they become separate species. Change on that scale is known as macroevolution.

In *Origin,* Darwin estimated that a new species might take between ten thousand and fourteen thousand generations to arise. Until recently, most biologists assumed it would take at least that many, or maybe even millions of generations, before microevolutionary changes led to the origin of new species. So they assumed they could watch evolution by natural selection, but not the divergence of one species into separate, reproductively isolated species. Now that view is changing too.

Not long ago, a young evolution-watcher named Andrew Hendry, a biologist at McGill University in Montreal, reported the results of a striking study of sockeye salmon [*see illustration on page 51*]. Sockeye tend to reproduce either in streams or along lake beaches. When the glaciers of the last ice age melted and retreated, about ten thousand years ago, they left behind thousands of new lakes. Salmon from streams swam into the lakes and stayed. Today their descendants tend to breed among themselves rather than with sockeyes that live in the streams. The fish in the lakes and streams are reproductively isolated from each other. So how fast did that happen?

In the 1930s and 1940s, sockeye salmon were introduced into Lake Washington, in Washington State. Hundreds of thousands of their descendants now live and breed in Cedar River, which feeds the lake. By 1957 some of the introduced sockeye also colonized a beach along the lake called Pleasure Point, about four miles from the mouth of Cedar River.

Hendry could tell whether a full-grown, breeding salmon had been born in the river or at the beach by examining the rings on its otoliths, or ear stones. Otolith rings reflect variations in water temperature while a fish embryo is developing. Water temperatures at the beach are relatively constant compared with the river temperatures. Hendry and his colleagues checked the otoliths and collected DNA samples from the fish—and found that more than a third of the sockeye breeding at Pleasure Point had grown up in the river. They were immigrants.

With such a large number of immigrants, the two populations at Pleasure Point should have blended back together. But they hadn't. So at breeding time many of the river sockeye that swam over to the

beach must have been relatively unsuccessful at passing on their genes.

Hendry could also tell the stream fish and the beach fish apart just by looking at them. Where the sockeye's breeding waters are swift-flowing, such as in Cedar River, the males tend to be slender. Their courtship ritual and competition with other males requires them to turn sideways in strong current—an awkward maneuver for a male with a deep, roundish body. So in strong current, slender males have the better chance of passing on their genes. But in still waters, males with the deepest bodies have the best chance of getting mates. So beach males tend to be rounder—their dimensions greater from the top of the back to the bottom of the belly—than river males.

What about females? In the river, where currents and floods are forever shifting and swirling the gravel, females have to dig deep nests for their eggs. So the females in the river tend to be bigger than their lake-dwelling counterparts, because bigger females can dig deeper nests. Where the water is calmer, the gravel stays put, and shallower nests will do.

So all of the beachgoers, male and female, have adapted to life at Pleasure Point. Their adaptations are strong enough that reproductive isolation has evolved. How long did the evolution take? Hendry began studying the salmon's reproductive isolation in 1992. At that time, the sockeyes in the stream and the ones at Pleasure Point had been breeding in their respective habitats for at most thirteen generations. That is so fast that, as Hendry and his colleagues point out, it may be possible someday soon to catch the next step, the origin of a new species.

And it's not just the sockeye salmon. Consider the three-spined stickleback. After the glaciers melted at the end of the last ice age, many sticklebacks swam out of the sea and into new glacial lakes—just as the salmon did. In the sea, sticklebacks wear heavy, bony body armor. In a lake they wear light armor [*see photograph on page 63*]. In a certain new pond in Bergen, Norway, during the past century, sticklebacks evolved toward the lighter armor in just thirty-one years. In Loberg Lake, Alaska, the same kind of change took only a dozen years. A generation for sticklebacks is two years. So that dramatic evolution took just six generations.

Dolph Schluter, a former finch-watcher from the Galápagos and currently a biologist at the University of British Columbia in Vancouver, has shown that, along with the evolution of new body types, sticklebacks also evolve a taste for mates with the new traits. In other words, the adaptive push of sexual selection is going hand-in-hand with natural selection. Schluter has built experimental ponds in Vancouver to observe the phenomenon under controlled conditions, and the same patterns he found in isolated lakes repeat themselves in his ponds. So adaptation can sometimes drive sexual selection and accelerate reproductive isolation.

EVOLUTION THAT'S FAST ENOUGH TO WATCH

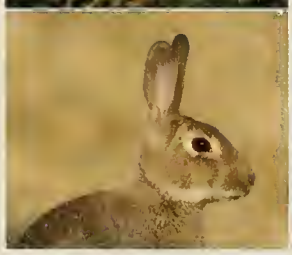
New England: marine snail
(Littorina obtusata)
Shell shape and thickness have changed in the past century, probably in response to being heavily hunted by crabs.

Bahamas: anole lizard
(Anolis sagrei)
Shapes of anole lizards' hind limbs changed and adapted to their new habitats when people brought the lizards to new island ranges.

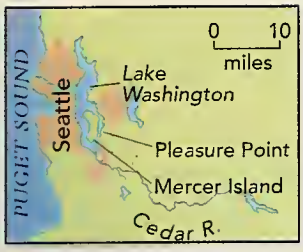
Florida: soapberry bug
(Jadera haematoloma)
Beak size of soapberry bugs grew significantly longer after its habitat was invaded by a non-native plant species with large fruit.

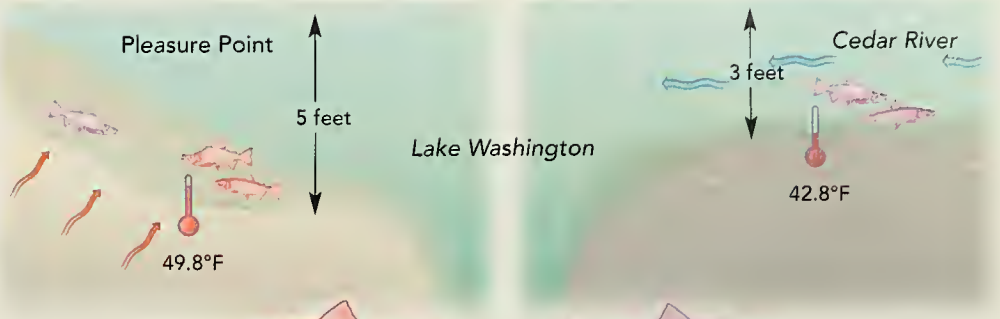
Hawai'i: scarlet honeycreeper, or *i'iwi*
(Vestiaria coccinea)
Bill length of the scarlet honeycreeper was reduced, and the bird switched to another source of nectar, as its favorite flowering plants, the lobelloids, began to disappear.

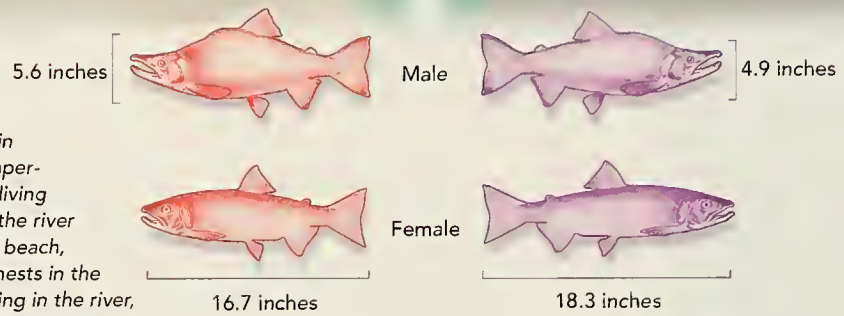
Nevada: mosquitofish
(Gambusia affinis)
Average length and fat content have shifted among distinct populations of mosquitofish, in response to variations in local environments.



Australia: wild rabbit
(Oryctolagus cuniculus)
Body size, body weight, and ear size changed among rabbits brought to Australia from Europe, in response to the unique climates of the Island Continent.







Some of the sockeye-salmon populations in and around Lake Washington have changed so much in the past half century that today they rarely interbreed. Salmon in Cedar River must contend with colder temperatures and stronger currents than the fish living at Pleasure Point Beach. Females living in the river have larger bodies than females along the beach, which enable them to dig slightly deeper nests in the gravel beds on the river bottom. Males living in the river, however, have more streamlined bodies (smaller body depth) than their counterparts along the beach, which may help them fare better in the strong currents. The beach salmon can dig shallower nests and still keep their eggs warmer than the river salmon because the sandy shore is insulated by upwelling ground water and is largely undisturbed by water movement.

There are other developments in the evolution watch, too many to mention in this small space. Some of the fastest action is microscopic. Richard Lenski, a biologist at Michigan State University in East Lansing, watches the evolution of *Escherichia coli*. Because one generation takes only twenty minutes, and billions of *E. coli* can fit in a petri dish, the bacteria make ideal subjects for experimental evolution. Throw some *E. coli* into a new dish, for instance, with food they haven't encountered before, and they will evolve and adapt—quickly at first and then more slowly, as they refine their fit with their new environment.

And then there are the controversies. Science progresses and evolves by controversy, by internal debate and revision. In the United States these days one almost hates to mention that there are arguments among evolutionists. So often, they are taken out of context and hyperamplified to suggest that nothing about Darwinism is solid—that Darwin is dead. But research is messy because nature is messy, and fieldwork is some of the messiest research of all. It is precisely here at its jagged cutting edge that Darwinism is most vigorously alive.

Not long ago, one of the most famous icons of the evolution watch toppled over: the story of the peppered moths, familiar to anyone who remembers biology 101. About half a century ago, the British evolutionist Bernard Kettlewell noted that certain moths in the British Isles had evolved into darker forms when the trunks of trees darkened with industrial pollution. When the trees lightened again, after clean air acts were passed, the moths had evolved into light forms again. Kettlewell claimed that dark moths resting on dark tree trunks were harder for birds to see; in each decade, moths of the right color were safer.

But in the past few years, workers have shown that Kettlewell's explanation was too simplistic. For one thing, the moths don't normally rest on tree trunks. In forty years of observation, only twice have moths been seen resting there. Nobody knows where they do rest. The moths did evolve rapidly, but no one can be certain why.

To me what remains most interesting is the light that studies such as Hendry's, or the Grants', may throw on the origin of species. It's extraordinary that scientists are now examining the very beginnings of the process, at the level of beaks and fins, at the level of the genes. The explosion of evolution-watchers is a remarkable development in Darwin's science. Even as the popular debate about evolution in America is reaching its most heated moment since the trial of John Scopes, evolutionary biologists are pursuing one of the most significant and surprising voyages of discovery since the young Darwin sailed into the Galápagos Archipelago aboard Her Majesty's Ship *Beagle*.

Not long ago I asked Hendry if his studies have changed the way he thinks about the origin of species. "Yes," he replied without hesitation, "I think it's occurring all over the place."

The Fossils Say Yes

The discovery of transitional forms has filled in some of the most talked-about gaps in the fossil record.

By Donald R. Prothero

It has been asserted over and over again, by writers who believe in the immutability of species, that geology yields no linking forms. This assertion . . . is certainly erroneous. . . . What geological research has not revealed, is the former existence of infinitely numerous gradations . . . connecting together nearly all existing and extinct species.
—Charles Darwin, the *Origin of Species*

When Darwin first proposed the idea of evolution by natural selection in 1859, the fossil record offered little support for his ideas. Darwin even devoted two entire chapters of the *Origin of Species* to the imperfection of the geologic record, because he was well aware it was one of the weakest links in his arguments. Then, just two years after his book was published, the first specimen of *Archaeopteryx* was discovered, hailed by many as the "missing link" between birds and reptiles. By the late nineteenth century, fossils helped demonstrate how the modern thoroughbred horse evolved from a dog-size, three-toed creature with low-crowned teeth. (The understanding of those fossils has since been much refined.)

Fossil evidence supporting evolution has continued to mount, particularly in the past few decades. DNA analysis, moreover, has helped make sense of how the evidence fits together in the family tree of life on Earth. Unfortunately, many people still think, quite erroneously, that the fossil record shows no "transitional forms." In large part, that misconception is the product of the campaign of misinformation—or disinformation—spread by the creationist movement.

The fossil record is far from perfect, of course. By most estimates, less than 1 percent of all the species that have ever lived are preserved as fossils. The reason for the scarcity is simply that the physical conditions needed to turn a dead organism into a fossil lasting millions of years are unusual.

Nevertheless, there are numerous excellent specimens that reflect transitional stages between major groups of organisms. Many more fossils exhibit how "infinitely numerous gradations" connect the species. The one caveat is that when a sequence of fossils appears to follow a direct line of descent, the chances are slim that they actually bear such precise interrelations. Paleontologists recognize that when one fossil looks ancestral to another, the first fossil is more safely described as being closely related to the actual ancestor.

The classic story of the evolution of the horse is a good example. The various known fossils were once arranged—simplistically, it turns out—into a single lineage leading from *"Eohippus"* to *Equus*. When more fossils became available, paleontologists revised that simple lineage. The fossils now give a branching and very bushy picture of equine evolution, with numerous now-extinct lineages living side by side. One quarry in Nebraska has yielded a dozen distinct species of fossil horses, in rock about 12 million years old. The earliest horses, such as *Protorohippus* (from early in the Eocene epoch, about 53 million years ago), are virtually indistinguishable from *Homogalax*, the earliest member of the lineage, which also gave rise to tapirs and rhinoceroses. Very early in my career, when I was taking an undergraduate paleontology class, I discovered just how tough it is to sort out those two ancient genera.

Ambulocetus natans, a whale the size of a sea lion that could probably walk on land as well as swim, may have been an ambush predator that trolled freshwater streams. Its fossil bones, dating to about 49 million years ago, were discovered in Pakistan in 1994. A. natans was a mammal, and is thought to be intermediary between early land carnivores and the more recent, fully aquatic whale. The painting is by Carl Buell.

Perhaps the most remarkable recent discoveries are the numerous fossils that connect whales with their four-legged terrestrial ancestors. If you look at dolphins, orcas, and blue whales, all fully aquatic animals, you would have a hard time imagining them walking on land. Yet even living whales retain vestiges of their hips and thighbones, deeply buried in the muscles along their spines. Paleontologists have known for a long time, on the basis of detailed features of the skull and teeth, that whales are closely related to hoofed mammals. But creationists long touted the absence of transitional fossils for whales as evidence against evolution.

The balance has now changed. In 1983 specimens of *Pakicetus* were discovered Pakistan in early Eocene beds about 52 million years old. Although the body of *Pakicetus* was primarily terrestrial, it had the skull and teeth of the ancient archaeocetes, the earliest family of whales—which swam the world's oceans in the Middle Eocene epoch, about 50 million years ago.

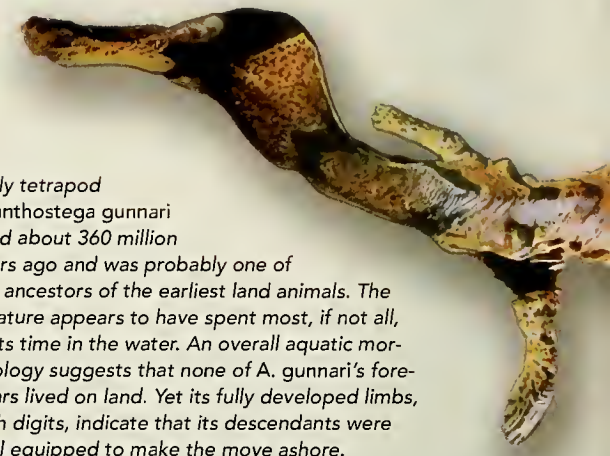
Then, in 1994, *Ambulocetus natans* (literally, the "walking whale that swims") was discovered, also in Pakistan [*see illustration below*]. The animal was the size of a large sea lion, with broad webbed feet on both fore- and hind limbs, so it could both walk and swim. Yet it still had tiny hooves on its toes and the primitive skull and teeth of the archaeocete. *Ambulocetus* apparently swam much like an otter, with an up-and-down motion of the spine, the precursor to the motion of the flukes of a whale's tail. In 1995 yet a third transitional creature was discovered, *Dalanistes,* with shorter legs than *Ambulocetus*, webbed feet, a longer tail, and a much larger and more whalelike skull.

Today more than a dozen transitional whale fossils have been unearthed—an excellent series for such rarely fossilized animals. DNA from the living species suggests that whales are descended from even-

toed hoofed mammals known as artiodactyls and, in particular, are most closely related to the hippopotamus. That hypothesis was dramatically confirmed by the discoveries in 2001 of the "double-pulley" anklebone, which is characteristic of artiodactyls, in two kinds of primitive whales.

Whales are not the only aquatic mammals with terrestrial ancestors. Modern sirenians (manatees and dugongs) are large, docile, aquatic herbivores that have flippers for forelimbs and no hind limbs. In 2001 Daryl Domning, a marine mammal paleontologist at Howard University in Washington, D.C., described a remarkably complete skeleton of *Pezosiren portelli* from Jamaican deposits about 50 million years old. That animal had the typical skull and teeth of a sirenian, and even the thick sirenian ribs made of dense bone, which serve as ballast. Yet it had four legs as well, all with feet, not flippers. Strong transitional fossils also link seals and sea lions to bearlike ancestors.

The origin of mammals is well documented. Mammals and their extinct relatives belong to a larger group known as the Synapsida. The earliest members of the group were once known as "mammal-like reptiles," even though they were not true reptiles but had already evolved to become a separate branch of animals. Among them was *Dimetrodon,* the largest predator on Earth about 280 million years ago. (Its sail-shaped back is familiar from toy-dinosaur kits for children, even though it was not a true dinosaur.) Although it was a primitive form, *Dimetrodon* had large, stabbing canine teeth and some of the specialized skull features of mammals.



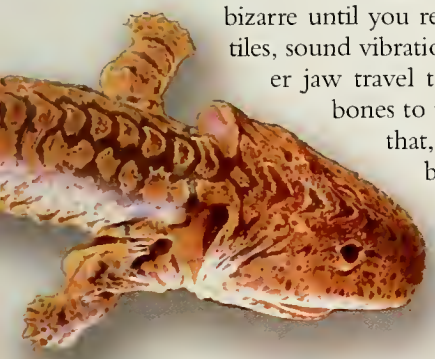
Early tetrapod Acanthostega gunnari *lived about 360 million years ago and was probably one of the ancestors of the earliest land animals. The creature appears to have spent most, if not all, of its time in the water. An overall aquatic morphology suggests that none of* A. gunnari*'s forebears lived on land. Yet its fully developed limbs, with digits, indicate that its descendants were well equipped to make the move ashore.*

For the next 80 million years, synapsids evolved into various wolflike and bearlike predators, as well as into an array of peculiar piglike herbivores. Along the way, they acquired progressively more mammalian features: additional jaw muscles that enabled complex chewing motions; a secondary palate covering the old reptilian palate and nasal region, which enabled them to breathe and eat at the same time; multicusped molars for chewing rather than gulping their food; enlarged brains; relatively upright (rather than sprawling) posture; and a muscular diaphragm in the rib cage for efficient breathing. There are even signs that they had hair, a quintessentially mammalian feature. The story of the synapsids culminates in the appearance of the earliest true mammals—shrew-size creatures—in fossil beds about 200 million years old in China, South Africa, and Texas.

Meat-eating dinosaur Sinornithosaurus millenia, *depicted in this artist's conception, could flap its forelimbs, which were covered in feathers. This species' fossil remains were unearthed in the Liaoning beds of northeastern China, along with several other birdlike dinosaurs. The animal was a transitional species, indicating that certain dinosaurs evolved to become birds.*

Among the most remarkable transformations that took place as the mammals emerged are the ones that can be observed in fossils of the lower jaws. In reptiles and primitive synapsids, the right and left lower jaws are each made up of a number of bones, one of which is the dentary, or tooth-bearing, bone. As synapsids

evolved, the dentary bone grew progressively larger until it took over the role of hinging the jaw to the skull. One of the other reptilian jawbones shrank until it vanished, whereas the other two shifted to the middle ear. There they became the anvil and the hammer, minute bones that transmit sound from the eardrum to the stirrup bone and, ultimately, to the inner ear. The shift in function seems bizarre until you realize that in reptiles, sound vibrations from the lower jaw travel through the skull bones to the inner ear, and that, along with the vibrations that travel from the eardrum, those vibrations are important sources of sensation.



Excellent "missing links" now exist for other major groups as well. Many fossil species show the transition from dinosaurs to birds. *Archaeopteryx,* for instance, discovered in Europe in Late Jurassic fossil beds about 150 million years old, had teeth. Slightly younger fossils, from the Chinese Lower Cretaceous, about 140 million years ago, had more birdlike features. *Sinornis,* for instance, had wings it could fold against its body, grasping feet with an opposable toe, and tailbones fused into a single element. *Confuciusornis* sported the first toothless beak. Lower Cretaceous rocks in Spain, about 130 million years old, have yielded *Iberomesornis,* which had a large, keeled breastbone to which powerful flight muscles were anchored. Still, the creature had the primitive long backbone of a dinosaur.

Such bird fossils are now joined in the web of ancient life-forms by numerous, recently discovered fossils of nonflying, nonavian dinosaurs, closely related to *Velociraptor* of *Jurassic Park* fame. Those fossils, such as *Microraptor* and *Caudipteryx,* had well-developed feathers, suggesting that feathers originally served other functions, such as insulation, long before they became useful for flight [*see "Bird's-eye View," by Matthew T. Carrano and Patrick M. O'Connor, May 2005*].

Another transition that is now well documented is the conquest of the land by the amphibians. For decades the only good intermediate fossil between fishes and amphibians was *Ichthyostega,* from the Late Devonian epoch (about 360 million years ago) of Greenland and Spitzbergen. Although *Ichthyostega* resembled many amphibians in having well-developed legs, a complete shoulder girdle, and hips fused to the backbone, it still had fishlike gill slits, a sensory system on its face for detecting underwater currents, and a long, fishlike tail fin.

More recent discoveries, such as *Acanthostega* from the same beds, show that the picture is much more complicated and interesting [*see illustration at left*]. *Acanthostega* had ear bones that were still adapted for underwater hearing, a longer tail fin than *Ichthyostega,* and better-developed gills, making it more primitive and aquatic than *Ichthyostega. Acanthostega* also had as many as eight toes on each of its four feet—rather than five, which became the standard in most early four-footed creatures. Apparently, its limbs were primarily adapted for swimming and walking along the bottom of a lake, rather than for crawling on land. Contrary to the popular story that four legs evolved because they enabled animals to crawl out onto the land (to escape drying ponds, chase new food sources, and so forth), it now appears that legs evolved for walking underwater (as most salamanders still do today). They became secondarily useful on land, because they were already in place.

What about the transitional forms that led to our favorite species, *Homo sapiens*? Not long ago, the fossil record of the human family was severely limited, and readily thrown into confusion by a single fraudulent "fossil" such as the 1912 hoax known as Piltdown Man. But in the past three decades new findings have exploded. In Chad, fossils of *Sahelanthropus* were discovered in beds between 6 million and 7 million years old. In Ethiopia, the new genus *Ardipithecus* and two new species of *Australopithecus (A. anamensis* and *A. bahrelghazali)* were unearthed in beds between 2 million and 5 million years old. Several species of our own genus, *Homo,* which goes back at least 2 million years, have now been identified.

In short, the human fossil record has become quite dense and complete, and the newfound samples have led to some surprises. For example, contrary to the expectations of earlier anthropologists, the fossils show that bipedalism arose before enlarged brains, which came quite late in human evolution.

The origin of vertebrates as a whole once also

Jawbones that once functioned only for eating evolved and later became ear bones needed for hearing.

Some major transitional forms of the human family, Hominidae, are represented by their skulls. In Darwin's day many naturalists were searching for a single "missing link" between humans and apes, but only one fossil species was known (Homo neanderthalensis, named in 1864). In the past 140 years, however, many near-human fossils have come to light, from the most recently discovered, the diminutive H. floresiensis, to the oldest among these species, Sahelanthropus tchadensis, whose hominid status is uncertain. Paleoanthropologists are hesitant to specify their exact evolutionary relations, but most agree that there were many human forms living contemporaneously. The thick yellow curves connecting the photographs of the skulls show one rough hypothesis about how the various species might be interrelated. But the illustration is intended only to represent some of the major hominid fossil finds, rather than serve as a definitive family tree.

presented a frustrating gap in the fossil record. Biologists could examine the many living animals (such as lancelets and sea squirts) that represented stages in the transition from the invertebrates to the earliest jawless fishes. Until recently, however, few good fossils had been identified from beds older than about 480 million years, near the beginning of the Ordovician period. What's more, they were only scattered bony scales and plates.

But recent discoveries in China from the Middle Cambrian epoch, between 510 million and 500 million years ago, have included not only the earliest relatives of the lancelets, but also some soft-bodied specimens that appear to be the earliest vertebrates. Thus, backboned animals can now be traced all the way back to the Cambrian, when most of the modern branches of animals originated.

As the 150th anniversary of Darwin's *Origin* approaches, the fossil evidence now available would make Darwin proud, rather than apologetic. Evolutionary biologists can also look forward to many more discoveries. Some will come as a surprise, like the early small-brained bipedal hominids. Some will force paleontologists to revise their ideas about evolutionary events. But the fossil record is no longer the embarrassment that it was in Darwin's day. □

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The Origins of Form

Ancient genes, recycled and repurposed, control embryonic development in organisms of striking diversity.

By Sean B. Carroll

When we no longer look at an organic being as a savage looks at a ship, as at something wholly beyond his comprehension; when we regard every production of nature as one which has had a history; when we contemplate every complex structure and instinct as the summing up of many contrivances, each useful to the possessor . . . how far more interesting, I speak from experience, will the study of natural history become!

—*Charles Darwin, the* Origin of Species, 1859

Darwin closed the most important book in the history of biology by inspiring his readers to see the grandeur in his new vision of nature—in how "from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved." For the next century, many kinds of biologists—geneticists, paleontologists, taxonomists—sought to test and expand that vision. The result of their work was the so-called modern synthesis, which organized the basic principles that have guided evolutionary biology for the past fifty years.

In spite of the labels "modern" and "synthesis," however, an important element was still missing from evolutionary theory. Biologists could say, with confidence, that forms change, and that natural selection is an important force for change. Yet they could say nothing about how that change is accomplished. How bodies or body parts change, or how new structures arise, remained complete mysteries.

Contemporary biologists are no longer savages staring at passing ships. In the past twenty years biologists have gained a revolutionary new understanding of how animal and plant forms and their complex structures arise and evolve. The key to the new understanding is development, the way a single cell becomes a complex, multibillion- or trillion-celled organism. And development is intimately linked to evolution, because all changes in form come about through changes in development. As an animal embryo grows, it must make countless "decisions" about the number, position, size, and color patterns of body parts. The endless combinations of such decisions made during development have led to the great variety of animal forms of the past and present.

Advances in the new science of evolutionary developmental biology—dubbed "evo-devo" for short—have enabled biologists to see beyond the external beauty of organic forms into the mechanisms that shape their diversity. Much of what has been learned, about animal forms in particular, has been so stunning and unexpected that it has profoundly expanded and reshaped the picture of how evolution works. In the same stroke, evo-devo delivers some crushing blows against the outdated rhetoric of those who doubt that complex structures and organisms arise through natural selection.

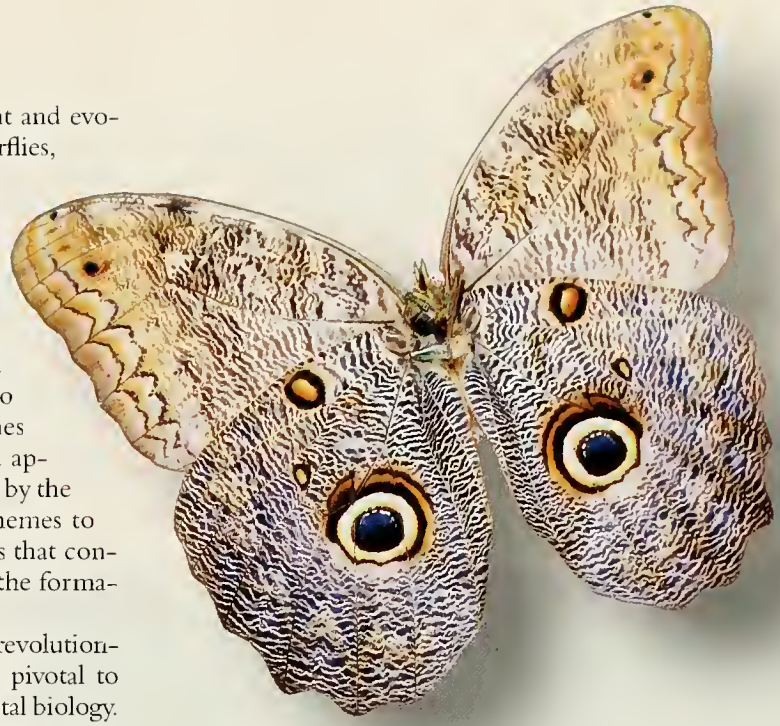
Darwin always insisted that embryology was crucial to understanding evolution. In a letter to the American botanist Asa Gray, shortly after the publication of the *Origin of Species,* he lamented, "Embryology is to me by far the strongest single class of facts in favor of change of forms, and not one, I think, of my reviewers has alluded to this." Yet the puzzle of how a single egg gives rise to a complete individual long stood as one of the most elusive questions in all of biology.

Many biologists once despaired that development was hopelessly complex. Each kind of animal, they thought, would require its own unique developmental explanation. With the advent of genetics, biologists came to realize that genes must be at the cen-

ter of the mysteries of both development and evolution. After all, butterflies look like butterflies, elephants look like elephants, and we look the way we do because of the genes we each carry. Those physical resemblances, and many other attributes, would surely be traceable to the genes within each species.

The challenge, given such a focus on genes, was that until relatively recently no one knew which of the thousands of genes in every animal shape its formation and appearance. The impasse was finally broken by the humble fruit fly. Geneticists devised schemes to find the relatively small fraction of genes that control the patterning of the fly's body and the formation of its parts.

Just as the invention of the telescope revolutionized astronomy, new technologies were pivotal to conceptual breakthroughs in developmental biology. New techniques for cloning and manipulating genes, together with new kinds of microscopes, enabled the body-building genes to be observed in action. Chemical changes in an embryo could be visualized long before the appearance of physical structures. Workers could thereby directly observe the earliest events in the formation of segments, limbs, or a brain [*see photomicrographs on next page*].



New patterns evolve when old genes "learn" new tricks. The eyespot patterns in the Morpho butterfly (below left) and the Caligo butterfly (above) evolved when genes that play a role in building other body parts and body patterns were co-opted. No new "spot" genes were involved.

I realize it may be hard to get excited about how a maggot develops. What can that teach us about the more majestic creatures people care about, such as mammals, the rest of the animal kingdom, our own species? Indeed, the common perception twenty years ago—reinforced by a wide cultural divide between biologists who worked with furry animals and those who worked with bugs or worms—was that the rules of development would differ enormously among such different forms.

The body parts of fruit flies, for instance, would not appear to have much in common with our own. We don't have antennae or wings. We walk around on two long, bony legs, not six little ones reinforced by an exoskeleton. We have a single pair of movable, camera-type eyes, not compound bug eyes staring out from a fixed position. Our blood is pumped by a four-chambered heart through a closed circulatory system with arteries and veins; it does not just slosh around in our body cavity. Given such great differences in structure and appearance, one might well conclude that there is nothing to learn from the study of a fly about how our own organs and body parts are formed. But that would be so wrong.

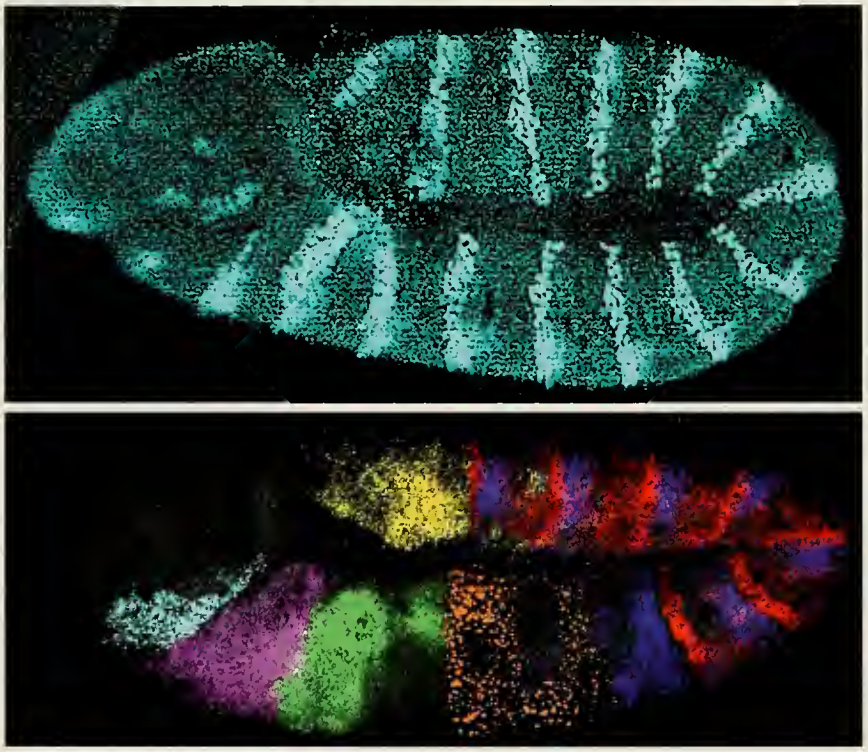
The first and perhaps most important lesson from evo-devo is that looks can be quite deceiving. Virtually no biologist expected to find what turned out to be the case: most of the genes first identified as body-building and organ-forming genes in the fruit fly have exact counterparts, performing similar jobs, in most mammals, including humans. The very first shots fired in the evo-devo revolution revealed that despite their great differences in appearance, almost all animals share a common "tool kit" of body-building genes. That discovery—actually a

series of discoveries—vaporized many previous ideas about how animals differ from one another.

For example, the origin of eyes has received a lot of attention throughout the history of evolutionary biology. Darwin devoted considerable effort in *Origin* to explaining how such "organs of extreme perfection" could evolve by natural selection. What has puzzled and intrigued biologists ever since Darwin is the variety of eye types in the animal kingdom. We and other vertebrates have camera-type eyes with a single lens. Flies, crabs, and other arthropods have compound eyes in which many, sometimes hundreds, of individual ommatidia, or unit eyes, gather visual information. Even though they are not close relatives of ours, squids and octopuses also have camera-type eyes, whereas their own close relatives, the clams and the scallops, have three kinds of eyes—camera, compound, and a mirror-type.

The great diversity and crazy-quilt distribution of eyes throughout the animal kingdom was, for more than a century, thought to be the result of the independent invention of eyes in various animal groups. The late evolutionary biologist Ernst Mayr and his colleague L. von Salvini-Plawen suggested, on the basis of cellular anatomy, that eyes had been invented independently between some forty and sixty-five times. Discoveries in evo-devo have forced a thorough reexamination of this accepted idea.

In 1994 Walter Gehring and his colleagues at the University of Basel, Switzerland, discovered that a gene required for eye formation in fruit flies is the exact counterpart of a gene required for eye formation in humans and mice. The gene, dubbed *Pax-6*, was subsequently found to play a role in eye formation in a host of other animals, including a species of squid [*see illustration on opposite page*]. Those discoveries suggested that despite their vast differences in structure and optical properties, the evolution of different eyes has involved a common genetic ingredient.



Chemical changes in various regions of an animal embryo (here, a developing fruit fly) reflect the activities of tool-kit genes; the changes can be imaged by laser-dye probes long before the physical form of an animal emerges. The upper image shows the pattern of activity of a single gene, Engrailed, *that marks the back end of each developing segment of the insect's body. In the lower image a different set of laser-dye probes reveal where each of seven* Hox *genes are active, corresponding to various parts of the body; for example, bright yellow indicates the segments that will form the fly's rear end, whereas fuchsia and light blue mark segments that will form mouthparts.*

Ernst Mayr once wrote:

> If there is only one efficient solution for a certain functional demand, very different gene complexes will come up with the same solution, no matter how different the pathway by which it is achieved. The saying "Many roads lead to Rome," is as true in evolution as in daily affairs.

But Mayr's view is incorrect. The architects of the modern synthesis expected the genomes of vastly different species to differ vastly. They had no idea that such different forms could be built with similar sets of genes. Stephen Jay Gould, in his monumental work, *The Structure of Evolutionary Theory*, saw the unexpected discovery of common body-building genes as overturning a major tenet of the modern synthesis.

There are not as many roads to Rome—or in other words, evolutionary paths to eyes and other complex structures—as biologists once thought. Natural selection has not repeatedly forged eyes from scratch. Rather, eye formation has common genetic ingredients, and a wide range of eye types incorporate parts, such as photoreceptor cells and light-sensing proteins, that have long been under the command of the *Pax-6* gene.

Other tool-kit genes have been identified that take part in building various kinds of limbs, hearts, and other structures. Because parts of the genetic tool kit

are shared among most branches of the animal kingdom, they must date back, at least, to some common ancestor of those branches. That would place their origin far back in time, before the Cambrian explosion that marked the emergence of large, complex animal bodies, more than 500 million years ago.

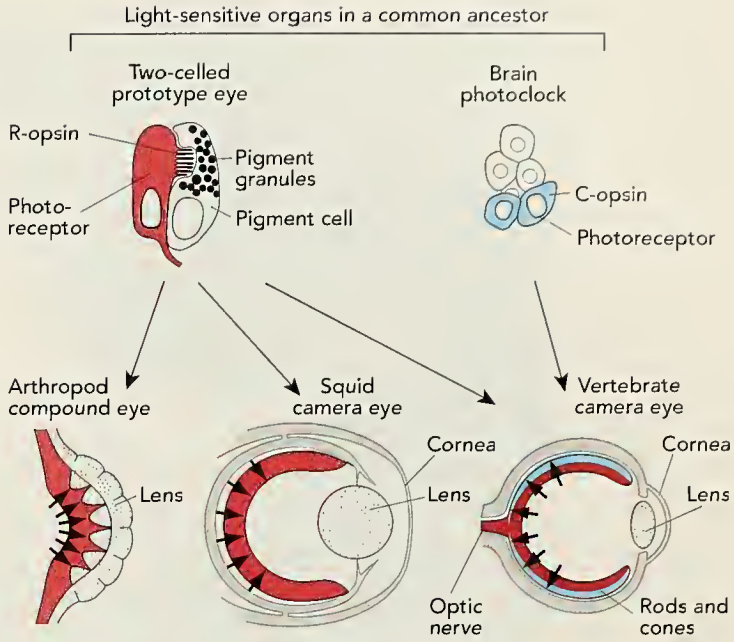
Here, then, is another somewhat counterintuitive insight from evo-devo: One might think that increases in animal complexity and diversity would be driven by the evolution of new genes. But it is now clear that most body-building genes were in place long before most kinds of animal body plans and complex organs emerged.

The discovery of such an ancient genetic tool kit, as exciting and rewarding as it is, raises a conundrum. If the sets of body-building genes among animals are so similar, how do such vast differences in forms arise?

Studies of many animal groups have shown that the diversity arises not so much from the content of the tool kit, but from how it is used. Various animal architectures are the products of applying the same genetic tools in different ways. For example, one of the most obvious features of large, complex animals such as vertebrates (fishes, amphibians, reptiles, birds, mammals) and arthropods (centipedes, spiders, crustaceans, insects) is their construction from repeating parts. Segments are the building blocks of arthropod bodies, vertebrae the building blocks of backbones. In both cases, important structures emerge from subsets of these building blocks—the many appendages of arthropods from their segments, the ribs of vertebrates from the vertebrae.

One of the dominant themes in the large-scale evolution of these animal bodies is change in the number and kind of repeating parts. The major features that distinguish classes of arthropods are the number of segments and the number and kind of appendages. Similarly, vertebrates differ fundamentally in the number and kind of vertebrae (cervical, thoracic, lumbar, sacral).

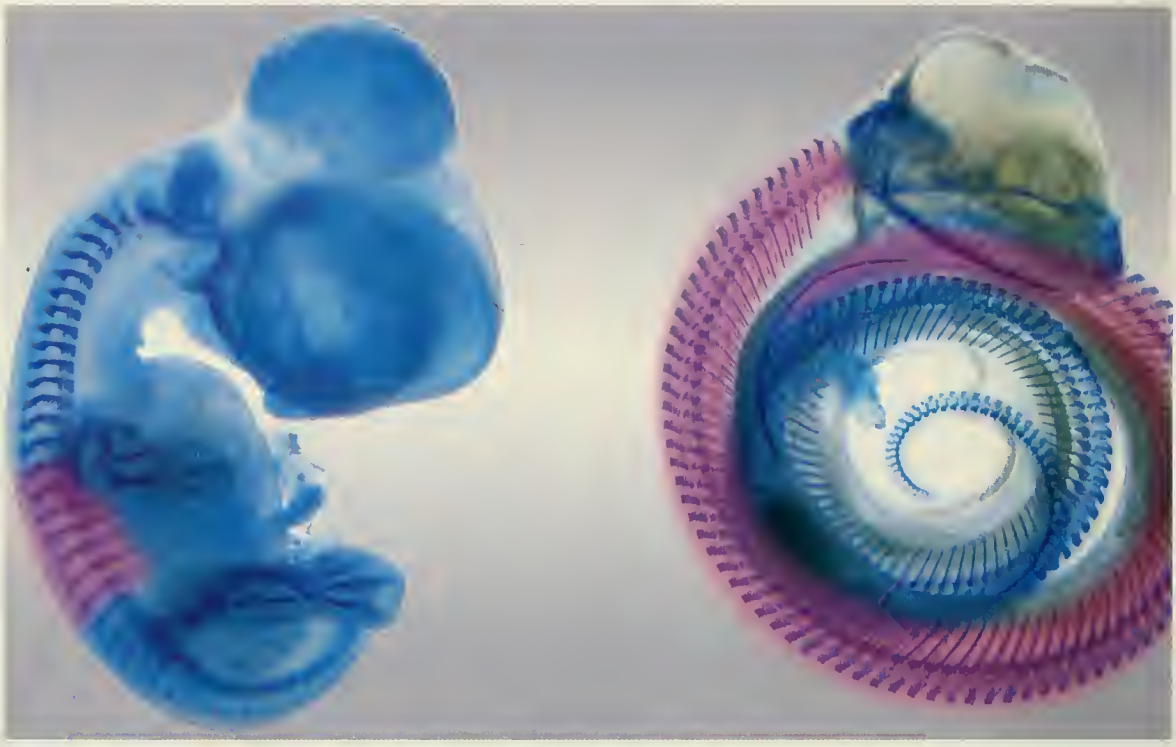
Extensive study of arthropod and vertebrate development has shown that those major features depend on a set of tool-kit genes called *Hox* genes. In general, *Hox* genes shape the number and appearance of repeated structures along the main body axes of both groups of animals. Individual *Hox* genes govern the identity of particular zones along that main body axis, and determine where various structures will form. A large body of work—on birds, frogs, mammals, and snakes, as well as insects, shrimp, and spiders—has proved that shifts in where *Hox* genes are expressed in embryos are responsible for the major differences among both vertebrates and arthropods.



Formation of a vast range of eye types—the camera eyes of vertebrates and squids as well as the compound eyes of flies—is controlled by a single gene, called Pax-6. Recognizing the role of the Pax-6 gene has been a key piece of evidence in tracing the evolution of the eye. Each animal eye evolved from simpler photoreceptive structures in a distant common ancestor of the arthropods, cephalopods, and vertebrates. The ancestor possessed two kinds of light-sensitive organs (upper half of diagram), each one endowed with a distinct type of photoreceptor, as well as with light-sensitive proteins called R-opsin and C-opsin, respectively. One organ was a simple two-celled prototype eye; the other, called the brain photoclock, was a part of the animal's brain and played a role in running the animal's daily clock. The arthropod and squid retinas (red) incorporated the photoreceptor from the simple prototype eye, whereas the vertebrate eye incorporated both kinds of photoreceptor into its retina (red and blue). Rods and cones, the photoreceptors of human vision, are shown in blue. Their orientation with respect to the light source (black arrows) is opposite that of the photoreceptors in the arthropod and squid eyes.

Those shifts account, for instance, for the way a snake forms its unique long body, with hundreds of rib-bearing vertebrae and essentially no neck, in contrast to other vertebrates [*see photograph on next page*]. The shifts explain why insects have just six legs and other arthropods have eight or more. The new imagery of evo-devo can pinpoint when and how the development of these animals diverges. The study of *Hox* genes has shown how, at an entirely new and fundamental level, these animals are the products of variations on ancient body plans—not wholly independent inventions.

Shifts in the expression of tool-kit genes during development not only account for large-scale differences in animal forms; they can also explain differences among closely related species, or even populations of the same species. For example, the three-spined stickleback fish occurs in two forms in



Hox genes determine the form, number, and evolution of repeating parts, such as the number and type of vertebrae in animals with backbones. In the developing chick (left), the Hoxc-6 gene controls the pattern of the seven thoracic vertebrae (highlighted in purple), all of which develop ribs. In the garter snake (right), the region controlled by the Hoxc-6 gene (purple) is expanded dramatically forward to the head and rearward to the cloaca.

many lakes in northern North America [*see photograph on opposite page*]. One is a short-spined, shallow-water, bottom-dwelling form. The other is long-spined and lives in open water. The two forms have evolved rapidly in these lakes since the end of the last ice age, about 10,000 years ago. The length of the fishes' pelvic spine is under pressure from predation. In the open water, long spines help protect the stickleback from being swallowed by large predators. But on the lake bottom, long pelvic spines are a liability: dragonfly larvae seize and feed on young sticklebacks by grabbing them by their spines.

Pelvic spines are part of the fishes' pelvic fin skeleton. Short spines in bottom-dwelling populations can be traced to a reduction in the development of the pelvic-fin bud in the embryo. David Kingsley, a geneticist at Stanford University, Dolph Schluter, a biologist at the University of British Columbia in Vancouver, and their collaborators have demonstrated that the change in spine length in short-spined sticklebacks can be traced to one specific tool-kit gene. The expression of the gene is altered so as to reduce the pelvic fin bud and, ultimately, the pelvic skeleton. The research has connected a change in DNA to a specific event in embryonic development, which in turn gives rise to a major adaptive change in body form that directly affects the ecology of a species.

The insights from the little three-spined stickleback may reach far beyond the fish's particular natural history. The pelvic fin is the evolutionary precursor of the vertebrate hind limb. Hind-limb reduction is not at all rare in vertebrates. In two groups of mammals—the cetaceans (dolphins and whales) and the manatees—the hind limbs became greatly reduced in size as the animals evolved from their land-dwelling ancestors into fully aquatic forms. Similarly, legless lizards have evolved many times. The study of sticklebacks has shown how natural selection can lead to changes in major features of animal skeletons in a relatively short time.

In addition to showing how evolution can change the number and kind of repeated body structures, evo-devo is shedding light on how novel structures and new patterns evolve. Bird feathers, for instance, are prominent examples of novelties that have emerged from changes in the ways tool-kit genes are expressed. So are the hands and feet of four-legged vertebrates, the insect wing, and the geometric color patterns on the wings of butterflies. It is easy to imagine that insects invented "wing" genes, or birds

"feather" genes, or vertebrates "hand" and "finger" genes. But there is no evidence that such genes ever arose. On the contrary, innovation seems to be more a matter of teaching old genes new tricks.

The implications of that insight are particularly significant for understanding human evolution. We humans have long supposed that we hold some unique position in the animal kingdom. Surely we must be the most genetically well-endowed species. Yet the reality, as molecular biologists now know from sequencing the genomes of our own and other species, is that the genes of human beings are very similar in number and kind to the genes of the chimpanzee and of the mouse—in fact, of all other vertebrates. No one should expect to account for the evolution of bipedalism, language, speech, or other human traits by finding novel genes. A more likely explanation will come from understanding how our "old" genes, shared with other primates, mammals, vertebrates, and more distant animal relatives, have found new applications.

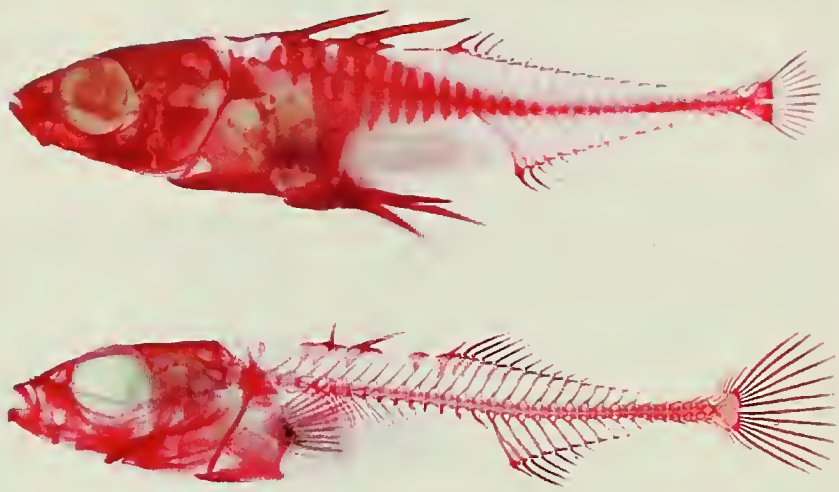
Darwin knew very well the difficulty people would have in picturing how complex structures or "contrivances" arose. In fact, as scholars such as the late Stephen Jay Gould and Randy Moore, a biologist at the University of Minnesota in Minneapolis, have pointed out, Darwin's choice of the term "contrivances," which appears fifteen times in *Origin,* was a deliberate one, used for rhetorical effect. It evoked a term the Reverend William Paley used in his 1802 book, *Natural Theology.* Paley saw the fashioning of "contrivances" in nature for specific purposes as revelations of God's design:

> Contrivance must have had a contriver; design, a designer. . . . It is only by the display of contrivance, that the existence, the agency, the wisdom of the Deity, *could* be testified to his rational creatures.

Paley's argument is the essence of the idea of "intelligent design," now being touted as a new "alternative" to evolutionary science. Darwin admired Paley's book, and declared that he had virtually committed parts of it to memory. He then structured much of his argument in *Origin* as a direct refutation of Paley. Where Paley compared the design of the eye with the design of the telescope, Darwin explained how such contrivances arose by natural selection, without the intervention of a divine contriver.

But Darwin's explanation, no matter how brilliant, was founded on the extrapolation of natural selection over vast periods of time. He had no access to fundamental knowledge about the development of eyes or their detailed evolutionary history. The new knowledge of tool-kit genes makes it clear how such complex structures are built. Evo-devo makes it possible to connect this everyday, observable, and experimentally accessible process to the long-term process of evolutionary change. Evo-devo shows how complex forms and structures evolve, not only in ways that lead from one species to the next, but also in ways, such as the making of body plans, that have shaped the major differences in the higher taxonomic ranks.

The major tenet of the modern evolutionary synthesis is that the evolution of forms above the species level ("macroevolution") can be extrapolated from processes operating at the level of populations, within species ("microevolution"). For those who have doubted that the modern evolutionary synthesis could explain macroevolution, the new insights from evo-devo should resolve the question. Through the lens of evolutionary developmental biology, biologists can finally see beyond external forms into the very processes that forge them, completing the picture of how the endless forms of nature have been, and are being, evolved. □



Major difference in the skeletal patterns of closely related populations reflects a difference in how a single tool-kit gene is used. Two forms of the three-spined stickleback fish (Gasterosteus aculeatus), which differ in the size of their pelvic fins, have repeatedly evolved in freshwater lakes. Long pelvic spines protect the open-water form from attack by other fish. Yet in the bottom-dwelling form (lower image), whose principal predator is dragonfly larvae rather than other fish, the tool-kit gene controlling the formation of the pelvic fin has been selectively turned off.

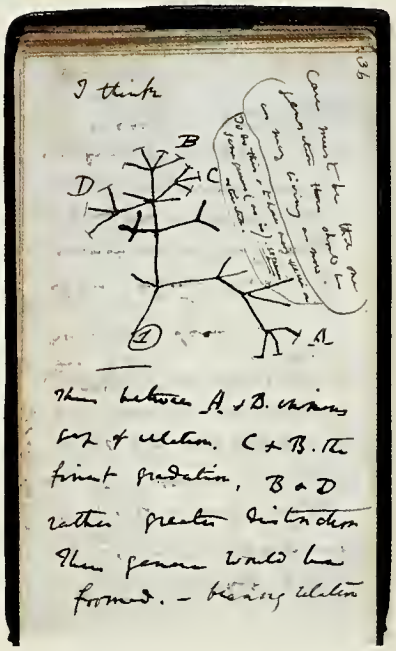
On Darwin's Shoulders

Computers and molecular techniques are ushering evolutionary biology into a new era.

By Douglas J. Futuyma

Charles Darwin's daring proposal that all living things have descended with modification from "a few forms or one" gained wide acceptance among biologists within twenty years of its publication in the *Origin of Species.* That vision of common ancestry revolutionized studies in comparative anatomy, comparative embryology, and taxonomy, and has become the unifying principle of all biology. But Darwin's seminal notion of natural selection—his truly original insight about the primary mechanism of evolution—was received more cautiously, and remains contentious among some biologists to this day.

Natural selection can preserve variations only if they are heritable, but Darwin (and his younger colleague, the naturalist Alfred Russel Wallace) had formulated the theory before anyone understood how heredity works. The missing piece of the puzzle turned out to be the discovery by the Austrian priest and botanist Gregor Mendel—published in 1865 but not appreciated until 1900—that heredity depends on the transmission of discrete particles, now called genes. By 1910 biologists recognized that genes can mutate at random into different forms, known as alleles. Joining the principles of genetics with Darwin's theory of natural selection initiated a second great episode of progress in evolutionary biology. Today the field is in the midst of a third flowering, and the pace of discovery and understanding is accelerating in realms that neither Darwin nor Wallace could have imagined.



Sketch in Darwin's own hand is the first known tree-like diagram of the relations among species. The drawing, made in the summer of 1837, depicts the relation of South American mammals to their fossil ancestors. Darwin shows common ancestors at the base of the trunk, and more recent species toward the branch tips. Branching has become a standard way to represent evolutionary relations.

The tale of Darwin's own intellectual journey into uncharted waters has reached mythical proportions, but the story of the second great episode deserves a brief retelling, because it bears on how biological science is conducted today. In the 1930s and 1940s, experimental geneticists, mathematical theorists, paleontologists, and systematists together forged the evolutionary synthesis, also known as the modern synthesis or synthetic theory of evolution. Among other things, they noted that when new alleles first arise, by mutation, they are very rare in a population. Some disappear right away, because they lead to the death of the individual carriers. Many are simply inconsequential—they do not even change the proteins for which they code—and do not affect

the survival and reproduction of the organism. Their frequency changes merely at random, a process known as genetic drift. A minority of them may increase by chance and become typical of the species.

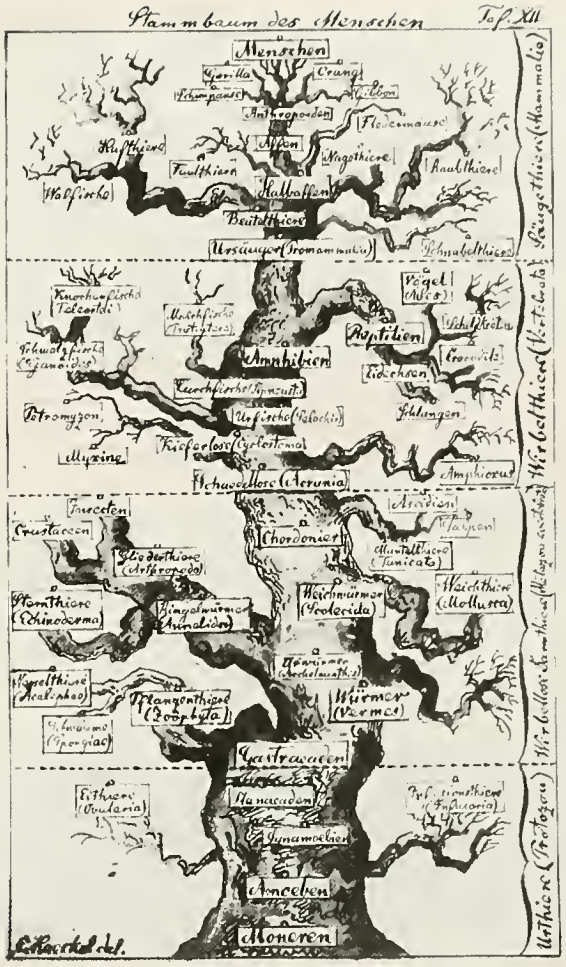
On occasion, alleles, often acting in combination, enhance the survival or reproduction of their carriers, and therefore increase in frequency within a population through the process of natural selection. Although natural selection can act in other ways, purifying or preserving older alleles in the population, the architects of the evolutionary synthesis emphasized its role in driving an increase in the frequency of new alleles that had arisen by mutation. The results are increasingly well-honed adaptations—those features of organisms that, as Darwin said, "so justly excite our admiration."

The scientists who forged the evolutionary synthesis agreed that speciation often occurs when various populations of a species become separated by mountains, rivers, unsuitable habitat, or other geophysical barriers. Genetic changes can then spread within the various population fragments without transferring from one fragment to another. An accumulation of such genetic changes would render the fragments incapable of interbreeding, through some behavioral or genetic incompatibility.

At that point they are considered different species. As time passes, these species, together with their various descendant species, continue to diverge. Proponents of the evolutionary synthesis, then, followed Darwin in envisioning macroevolution—speciation and evolution in the long term—as a gradual, incremental process.

Evolutionary research in the 1950s and 1960s was directed largely at testing the principles of the evolutionary synthesis. Biologists who focused on so-called microevolutionary changes—observable, short-term genetic processes within small populations—generally confirmed its validity. One of the most important accomplishments of this period was the proof that most characters are genetically variable within a population. Thus, when environments change, adaptation often proceeds rapidly without new mutations, because alleles that prove to be advantageous are already present in the population.

The third and current episode of progress in evolutionary biology was launched in the late 1960s, when two new technologies exploded on the scene. One was the ready availability of powerful computers and information processors. For biologists, this technology opened the door to compiling and analyzing databases of ever greater size and complexity, in ways that had previously been impractical or even impossible. The second new technology



Tree of life, according to the German zoologist Ernst Haeckel, had bacteria (Moneren) at its base and humans (Menschen) and great apes (Affen) at the topmost branches. This drawing, from Haeckel's The Evolution of Man *(1874), was one of the first to depict the theory that humans and apes shared a close common ancestry.*

was biomolecular analysis, first applied to determining the sequences of amino acids that make up certain proteins, such as hemoglobins. Today that technology has blossomed into a sophisticated array of methods for sequencing DNA and, in general, for studying how genes work.

One key application of computers has been to analyze the phylogenetic relations between organisms—"family trees"—showing which species are more closely and which more distantly related. Before the computer, such family trees were based on relatively few details of anatomy, which often were insufficient for firm conclusions about relationships. High-speed computing enabled biologists to analyze many more characters of the various species, including DNA and protein sequences, which are often easier to interpret than anatomical features.

When relationships among many species are an-

alyzed, the number of possible family trees that must be evaluated is huge. Computers also made it possible to compare them with one another and to determine the most parsimonious, or least tortuous, way of mapping the interspecies relations. The analysis of similarities and differences at the molecular level confirmed some traditional ideas about relations among various species, but it also brought surprises. For example, protein comparisons showed that humans share an immediate common ancestor with chimpanzees and gorillas. It had been thought previously that humans were equally related to all the great apes.

With the ability to determine amino-acid sequences, it was also natural to ask, how many differences are there between corresponding sequences of two related species, and how do those counts compare with paleontologists' estimates of how long ago the two lineages diverged? When the data were plotted, they suggested, surprisingly, that the rate of molecular evolution is roughly constant. Evolutionary biologists knew that the rate of evolution of anatomical features varies greatly from time to time and species to species, and so they had assumed that proteins would conform to the same pattern.

If females from distinct groups come to prefer males with different traits, the differences between the two groups may become increasingly exaggerated.

To account for the constancy, the Japanese population geneticist Motoo Kimura proposed his "neutral theory of molecular evolution." According to the theory, many changes in the genome are caused by genetic drift rather than by natural selection, and simply have no effect on the organism. Genetic drift operates at about the same rate all the time, unlike natural selection, which drives changes mostly when environments change [*see "Tuning In," by Carl Zimmer, September 2001*]. Kimura's hypothesis has stood up to nearly three decades of testing, and it has become an important addition to the evolutionary synthesis, which minimized the importance of genetic drift.

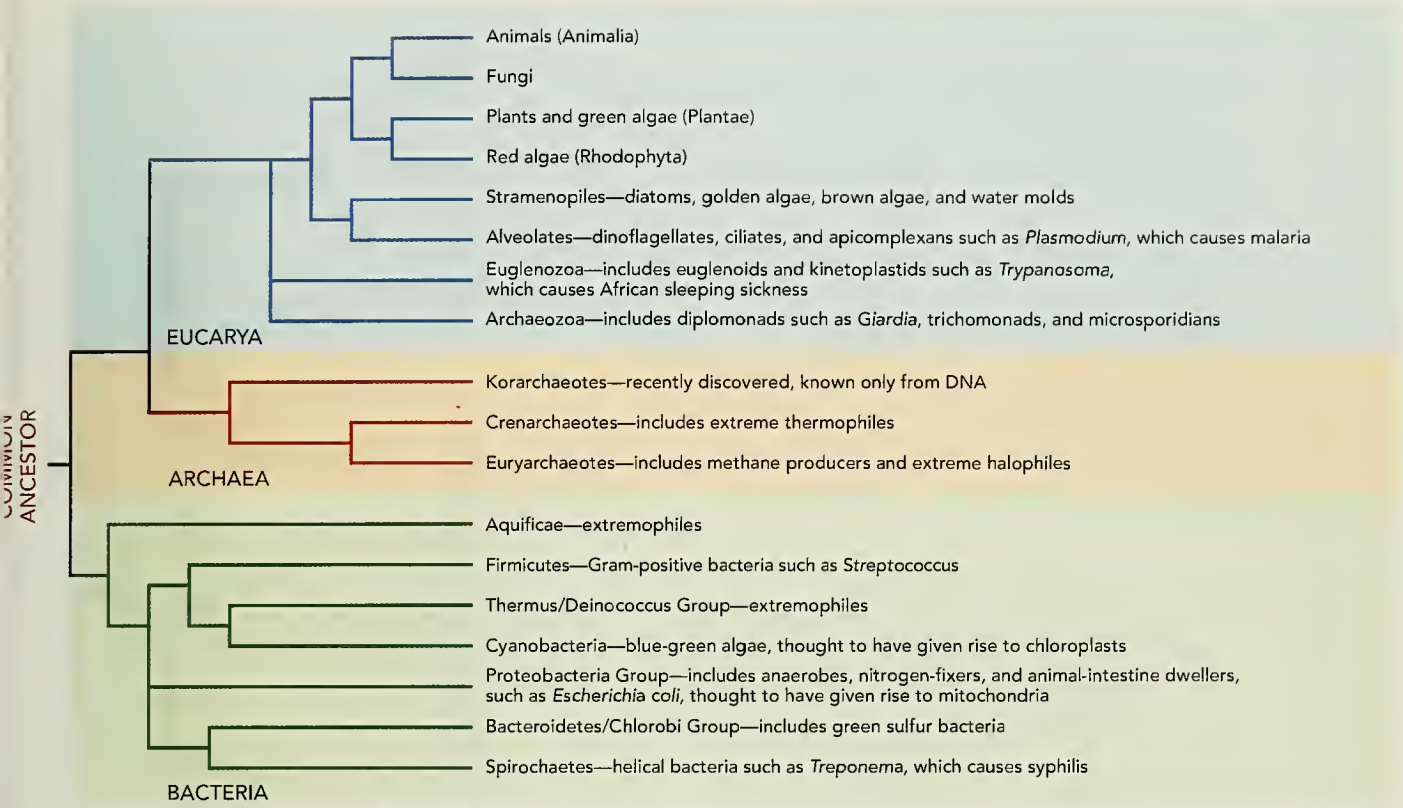
At about the same time Kimura developed his theory, the geneticists Richard C. Lewontin and John L. Hubby, both then at the University of Chicago, tested certain proteins for uniformity within a species. Using a technique called protein electrophoresis to examine proteins in the fruit fly *Drosophila pseudoobscura,* they discovered that about a third of them displayed differing genetic variants. That was far more variation than anyone had expected. Moreover, other investigators found similar levels of variation in almost every other species they examined, including humans. Were the variations neutral ones, of the kind suggested by Kimura, or were they maintained by natural selection, perhaps as adaptations to variations within a species' environment? The current evidence suggests that both explanations apply, but their relative importance remains uncertain.

The variations themselves have proved useful as genetic markers, helping answer questions that previously had been intractable: To what extent are geographically separate populations of a species also separate genetically? Do closely related species differ by few or many genes? Do genes "leak" between related species?

In the 1990s protein-based studies were largely replaced by analyses of the sequence of base pairs, the building blocks that make up DNA. Such analyses were made possible by another technological breakthrough, the polymerase chain reaction (PCR), invented in 1983 by Kary Mullis. From one or a few DNA molecules, PCR gives rise to huge numbers of copies, which are necessary to obtain the sequence of base pairs. The technique provides DNA data for studies of phylogenetic relationships among species and for investigating natural selection and genetic drift within species. DNA sequences of entire genomes—from microorganisms of many kinds and from people, mice, and a growing number of animal and plant species—are making it possible for geneticists to study the effects of natural selection and genetic drift on thousands of genes and to trace the origins of new kinds of genes with novel functions.

Perhaps the most exciting new field made possible by the new molecular technologies is evolutionary developmental biology ("evo-devo"). Its focus is to explore how the pathways of embryonic development evolve and give rise to major changes in adult morphology [*see "The Origins of Form," by Sean B. Carroll, page 58*]. For example, geneticists now know that certain genes, including those called *Hox* genes, regulate the activity of other genes. The *Hox* genes can cause some structures to repeat themselves, creating multiple segments, legs, or vertebrae.

Some research in evo-devo is leading to a moderate reevaluation of traditional ideas. For example, according to the prevailing view, morphological and other features of the organism evolve by a slow accumulation of slight incremental changes. But some



Simplified, contemporary tree of life divides all life-forms into three domains—Eucarya, Archaea, and Bacteria. The diagram reflects the current view that animals are more closely related to fungi and to the domain Archaea than they are to Bacteria. Because the diagram includes only the largest groupings of life from a "top-down" perspective, it does not depict the enormous diversity of plant and animal life. It is based on a more extensive tree of life compiled by Joel Cracraft of the American Museum of Natural History.

studies have shown that just a few gene differences, each with disproportionately large effects, can cause major differences in the characteristics of closely related species. Darwin's principle of gradual change still holds overall, but not all change is as gradual as biologists used to think.

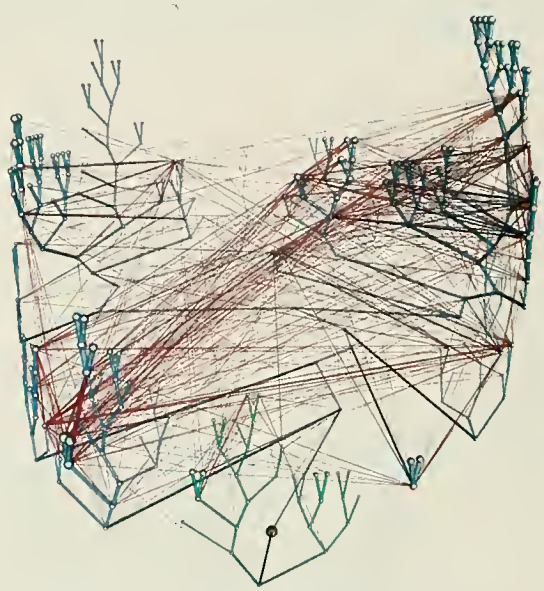
Among the most important questions still being addressed in studies of evolution is how speciation takes place. In particular, what gives rise to reproductive isolation among populations of a single species? Many biologists, following Darwin's lead, have assumed that divergence into separate species is brought about as natural selection acts on reproductive traits. Until recently, though, there have been precious few data to clarify how or why that may happen.

Most species differ from each other in characteristics that adapt them to somewhat different habitats, food, and other environmental factors. One hypothesis is that reproductive isolation, leading to speciation, is precipitated by characteristics that are simply adaptations to distinct environments. For example, Daniel J. Funk, a biologist at Vanderbilt University in Nashville, Tennessee, and Patrik Nosil, a graduate student in biosciences at Simon Fraser University in Burnaby, British Columbia, tested that hypothesis in studies of leaf beetles and stick insects. They observed how much interbreeding took place between geographically distinct populations. They found that if two such populations were adapted to different species of host plants, the insect populations were less likely to interbreed than if they were adapted to the same plant species. The finding is consistent with the idea that speciation can be a side effect of specialized ecological adaptation.

An alternative proposal is that species can arise because of sexual selection, a particular kind of natural selection. Female preference for males with certain features can cause males with even more exaggerated features to be more reproductively successful. If females from distinct populations prefer males that display slightly different characters, such as col-

oration, the differences between the two groups may become increasingly exaggerated, until the males of one group cease to have any sex appeal to the females of the other.

Sexual selection is thought to be more intense in polygamous than monogamous species. In one study, the diversity of species was compared among several pairs of "sister clades" of birds—lineages that share an immediate common ancestor. Shaibal Mitra, a graduate student in evolutionary biology at the University of Chicago at the time the work was done, and his colleagues found that a clade of polygamous species, such as birds of paradise, usually has diversified into more species than its monogamous sister clade, such as the crowlike manucode birds. The pattern strongly suggests that sexual selection contributes to the origin of species.



Three-dimensional "net of life," mapped by computer, depicts relations among Bacteria (nodes on blue branches) and Archaea (nodes on green branches). The diagram graphically illustrates how life evolves both vertically, through gene transfer from parent to offspring, and horizontally (red lines), through the exchange of genes between distantly related microorganisms. The orange sphere represents the common ancestor of the two groups. The diagram was made by Christos A. Ouzounis and his colleagues at the European Molecular Biology Laboratory in Cambridge, England.

Various knotty problems continue to puzzle evolutionary biologists. Why, for instance, do so many species reproduce sexually rather than asexually? Most sexually reproducing species produce roughly equal numbers of sons and daughters, and so only half those progeny (the female half) produce babies. In contrast, all the offspring of an asexual female are baby-producing females. Other things being equal, the second means of reproduction should quickly dominate. Because that does not happen, there must be a powerful compensating advantage to sexual reproduction. There are even some species, such as whiptail lizards, whose populations include both sexual and asexual types of females, yet the asexual type does not seem to come to dominate the population.

Sexual reproduction does provide a species with adaptive flexibility, because it is constantly giving rise to new combinations of genes. Thus sex may help prevent or forestall extinction if a species' environment changes. As one might expect, species with very old asexual lineages are rare. But natural selection has no foresight. It cannot be expected to provide a species with a feature that acts only as an insurance policy against some future contingency. Darwinian natural selection operates on differences between individuals of a species in features that affect individual reproduction or survival.

Plenty of advantages to sexual reproduction have been proposed. One is that the shuffling of genes in a sexual species can separate harmful mutant genes from advantageous genes, enabling natural selection to purge the harmful ones more efficiently. Another is that defective genes are often repaired during sexual reproduction. And a third is that sexual females may produce more variable offspring, which can live and reproduce themselves in a greater variety of circumstances, so that on average, sexual females may leave more surviving offspring.

The more one learns about evolutionary mechanisms, the more questions one can pose. How could alternative gene splicing have evolved, whereby a single gene encodes two or more different proteins? What prevents transposable DNA sequences, which can multiply within the genome and infest it like weeds in a garden, from taking over the genome? How do plant and animal species manage to survive, despite the high rate at which bacterial and viral parasites can evolve and overcome their hosts' defenses? Are there general rules that can explain why some groups (beetles, flowering plants) have diversified so much more than others (scorpionflies, cycads)?

Delve into almost any subject, no matter how specialized and arcane, and you will find biologists working on unanswered questions, and usually arguing with others about the likely answers. As science presses beyond the limits of the known and the understood into the unknown and the enigmatic, such disagreements reveal not that the science is faulty, but rather that it is alive and well. □

World's Most Valuable Timepiece Disappears

Back in 1933, the single most important watch ever built was engineered for a quiet millionaire collector named Henry Graves. It took over three years and the most advanced horological technique to create the multifunction masterpiece. This one-of-a-kind watch was to become the most coveted piece in the collection of the Museum of Time near Chicago. Recently this ultra-rare innovation was auctioned off for the record price of $11,030,000 by Sotheby's to a secretive anonymous collector. Now the watch is locked away in a private vault in an unknown location. We believe that a classic like this should be available to true watch afficionados, so Stauer replicated the exact Graves design in the limited edition Graves '33.

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27 jewels and 210 hand-assembled parts drive this classic masterpiece.

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No Links Missing

By Robert Anderson

On a windswept stretch of Interstate 10, between Los Angeles and Palm Springs; a forty-five-foot concrete sauropod overlooks the speeding cars. Behind it looms an even taller *T. rex*. Built by a former amusement park sculptor in the 1960s, these extraordinary examples of roadside kitsch are sized so that we'll pull over and spend a few dollars. I always used to let my kids stop in the gift shop, alluringly located inside the belly of the *Apatosaurus*.

But no more. Creationists have bought the dinosaurs. The store's prehistoric toys now carry a warning label: "Don't swallow it! The fossil record does not support evolution." And at its cute Web site for kids (cabazondinosaurs.com), they ask: "Is there a Designer? If a plane or car needs a designer, why would life need anything less?"

I was sad to lose the dino stop, but I realized the new owners had found the perfect outlet for their cause. If you're going to attack a basic tenet of modern science, do it through tacky highway attractions. I'm sure the people at the National Center for Science Education (www.ncseweb.org) would agree. A clearinghouse for information to help educators and the public understand and counter the "intelligent design" movement, NCSE is not opposed to creationists espousing their pseudoscientific views, as long as they don't carry out their threat to do so in public-school science classes. The center takes that well-funded threat seriously.

On its home page I was drawn to the news section that tracks the latest victories and losses in the ongoing culture war. One story, from the Kansas newspaper *Lawrence Journal-World*, grabbed my attention because of the callout, "Standards debate harming Kansas's reputation" (by the time you read this, it may no longer be on the home page but in the "News Room," the site's news archive). Click on "Story in the *Lawrence Journal-World*" to find University of Kansas provost David Shulenburger's comment that the debate over how evolution is taught has made it "tougher to recruit faculty and top students." I hope officials in other states read that one.

To find out how the controversy is playing out in your part of the country, click "News Room" on the bar near the top, and you will find an article archive you can search by state and year. The "Resources" page will answer many questions about how to defend science from fundamentalist attacks. Items include court decisions against teaching creationism as science and tips on testifying at local school board meetings. Or hit "Links" for an annotated list of sites relating to evolution.

One of the best Web sites for basic explanations of evolutionary concepts is run by the Museum of Paleontology of the University of California, Berkeley (www.ucmp.berkeley.edu). Click on "Understanding Evolution" and go to "Relevance of Evolution." Here you will find specific examples of why the teaching of evolution is important: not only does it best explain the evidence; it is also the key to making informed decisions in many fields crucial to our nation's future.

Before you argue with someone who insists there is no proof of evolution, return to the "Understanding Evolution" home page and click on "Evidence." There you'll find plenty of powerful examples [*see also "Evolution in Action," by Jonathan Weiner, page 47*]. My favorite is an *Aetiocetus* skull, a 25-million-year-old intermediate ancestor of the whale, which refutes the creationist claim that transitional fossils don't exist [*see also "The Fossils Say Yes," by Donald R. Prothero, page 52*]. This fossil skull, with its nostrils in the middle, is a halfway point: 50 million years ago, the nostrils of an earlier ancestor, a land-dwelling mammal, were at the tip of the snout; today the whale's nostrils are at the top of the head. At the end of this section, "Evidence by Example" explores instances of evolution in progress.

The PBS site pbs.org/wgbh/evolution offers the remarkable "Evolution Library," with hundreds of multimedia files, including videos, interviews, and interactive programs. At the Web site of the National Academy of Sciences (www.nationalacademies.org/evolution), five online publications designed especially for teachers are available. For those interested in debating the intelligent-design crowd, try talkdesign.org for critiques of their arguments. Finally, at this magazine's own Web site (naturalhistorymag.com), click on the special report "Intelligent Design?" Three scientists rebut three ID proponents. Published three years ago, it is even more relevant today. With a nod from the current U.S. president, creation "science"—in the guise of intelligent design—is poised to spread well beyond Kansas and roadside dinosaurs, diminishing the scientific reputation of an entire nation.

ROBERT ANDERSON is a freelance science writer living in Los Angeles.

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OUT THERE

The Galaxies, They Are A-Changin'

The cosmos evolves, just like life on Earth.

By Charles Liu

Evolution happens—and not just to life on Earth. Planets evolve. Stars evolve. Galaxies evolve. Even the universe itself evolves. Now, before you imagine celestial objects undergoing a surreal form of natural selection, I should clarify what we astronomers mean by evolution: a continual change in the properties of a complex system over a long time.

Biological purists might dismiss this kind of evolution as nothing more than ordinary change. In astronomy, though, the realization that anything out there has ever changed at all has been as revolutionary to the understanding of the cosmos as Darwinian evolution has been to the understanding of life here on Earth. Until the 1920s, the only available accounts of the origins of the universe were the millennia-old, faith-based stories promulgated worldwide. No scientifically testable models were seriously considered until the American astronomer Edwin P. Hubble first observed that the universe was expanding. Only then did astronomers accept that the cosmos has been evolving since the moment of its origin.

Composite image, in visible and infrared light, of the cluster of galaxies known as CL 1216, some 8 billion light-years from Earth, yields clues to the evolution of the universe. Clusters of galaxies are relatively rare, but the more distant clusters appear to have fundamentally different properties from the ones closer by.

In succeeding decades, overwhelming scientific evidence has confirmed that the universe does indeed change systematically with time. The work of Hans A. Bethe and his collaborators, for example, showed that nuclear fusion in the stars transforms hydrogen into helium and other elements. The cumulative effect, over billions of years, is to change the elemental composition of the universe.

A second major kind of evolution was confirmed in 1965, with the discovery of the cosmic microwave background radiation by Arno A. Penzias and Robert W. Wilson. The finding cemented the big bang theory, according to which the universe began as supersmall and superhot, and has since grown superlarge and supercold.

One corollary to big bang evolution is that astronomers expect to see a complex interplay between objects moving away from one another with time, reflecting the expansion of the cosmos, and objects moving toward one another, because of gravity. Consider, for example, rich clusters of galaxies—collections of hundreds or thousands of galaxies, which you might think would all be moving apart. Instead they are held close together by their mutual gravitational pull. Such clusters are relatively rare—fewer than one out of ten galaxies in the universe belongs to a rich cluster—but they serve as anchor points for the large-scale structure of the universe, helping arrange cosmic matter in an intricate web because of their gravitational clout.

It follows, then, that one key element of cosmic evolution is the aging of rich clusters. But do galaxies in such clusters age and change the same way as the rest of the galaxies in the universe? Rose A. Finn, an astronomer at Siena College in Loudonville, New York, and her colleagues are busy answering that question.

Astronomers have a decided advantage over paleontologists when it comes to studying relics of prehistory. The organisms of the distant past have undergone profound changes, physically and chemically, in becoming the fossils we find on Earth today. But the stars, galaxies, and quasars that we astronomers observe appear just as they were in the distant past, not as silicon-impregnated shadows of their former selves.

Paleontologists, for their part, have the luxury of being able to pick up and hold or at least touch their fossils, whereas astronomers must engineer tools—telescopes and cameras—to study their subject matter remotely. Finn and her collaborators trained the 6.5-meter MMT telescope on Mount Hopkins, Arizona, on five clusters of galaxies, each about 8 billion light-years from Earth. With images made in visible and in infrared light [*see photograph on this page*], they measured the rates of new star formation in the clusters' galaxies—the most important long-term indicator of how galaxies evolve.

Then, using computer models of how stars evolve after they're born,

they extrapolated their results forward to predict what the clusters' galaxy populations might look like some 2 billion years later. Finally, they compared those results with the galaxy populations of younger clusters, each about 6 billion light-years from Earth. Reporting on results from three of the clusters they've analyzed so far, Finn shows that after 2 billion years, the galaxy population in the more distant clusters could indeed evolve to look much like the population of clusters closer by.

Of course, uncertainties abound in this conclusion. A lot can happen in 2 billion years. Even more relevant is the uncertainty of comparing objects that can be observed at only one point in their life history with other objects observed at a different age. It's like taking a snapshot of all the people in Grand Central Terminal, and then trying to deduce whether the children will one day look like the adults. On a general level, you can be pretty sure the answer is yes, but you'll have no clue about the details unless you're lucky enough to catch an entire family of close relatives, of various ages, walking together. And there's no easy way to know whether that's the case.

Do those uncertainties imply that Finn's study falls short of an absolute truth? Yes. Does that mean the study failed? Of course not. Science is a process that often moves gradually, in a series of ever-more-precise refinements. As more facts are gathered, more models posited, more predictions tested, and more theories built, the constraints on the possible truths become ever more rigorous, and nature comes into ever sharper focus. Future investigators will build on Finn's work, and even the uncertainties themselves, if estimated with precision, will guide their explorations into the unknown. Thanks to the efforts of those who study cosmic evolution, all of humanity will continue to move closer to grasping the evolving, ever-changing grandeur of our universe.

CHARLES LIU is a professor of astrophysics at the City University of New York and an associate with the American Museum of Natural History.

THE SKY IN NOVEMBER

By Joe Rao

Mercury will be hard to see early this month. Look for it with binoculars, about twenty-three degrees below and to the right of Venus shortly after sunset. Viewers in the south will have the best chance to spot the planet this month, because it shines higher there than it does in the north. The star Antares—the red "heart" of the constellation Scorpius, the scorpion—is to Mercury's left. The planet reaches greatest eastern elongation, 23.5 degrees from the Sun, on the 3rd. That same evening, you may be able to glimpse a sliver of the crescent Moon hovering below Mercury.

Venus boldly shows itself this month, and if you know where to look (forty degrees to the left of the setting Sun, and twenty degrees above the horizon), you may even be able to catch sight of the "evening star" before sunset. The brilliant planet climbs higher in the twilit sky throughout the month; it also brightens slightly, as it catches up to Earth in its orbital race around the Sun. Like Mercury, Venus reaches its greatest elongation, forty-seven degrees east of the Sun, on the evening of the 3rd. Two nights later Venus and the crescent Moon pair up in the west-southwestern sky.

Viewers aided by a telescope will see that several days before reaching greatest elongation, Venus reaches dichotomy—it appears to be exactly half-lit.

Mars reaches opposition to the Sun on the 7th, making it visible all night. In fact, once Venus sets, Mars is the night's premier celestial attraction. The Red Planet is slowly moving retrograde, or westward, through the constellation Aries, the ram. Between the 7th and the end of the month, Mars also loses nearly half its brightness, diminishing rapidly from magnitude −2.3 to −1.6 as it recedes from the Earth. At the same time, though, Mars is becoming well-positioned for convenient viewing. On the 14th Mars will be situated below and to the left of an almost full Moon.

Telescopic observers will have a good chance to take in Mars's bright polar areas, dark surface markings, white clouds, and yellow dust storms.

At the onset of November, Jupiter doesn't rise until dawn is well advanced, at about 5:45 A.M. But it rises about three minutes earlier each morning thereafter and gradually becomes visible in a darker sky. By midmonth the planet rises before the beginning of morning twilight, and at month's end it rises at about 4:20 A.M. A waning crescent Moon pays Jupiter a visit on the mornings of the 28th and 29th.

Saturn, in the faint constellation Cancer, the crab, rises just before 11 P.M. at the beginning of the month; by month's end it rises two hours earlier. At midmonth the ringed planet appears as a bright yellow-white "star," shining at magnitude 0.3. On the evening of the 21st Saturn lies to the right of a waning gibbous Moon. Throughout the month the great ring system is tilted about eighteen degrees to our line of sight, and so Saturn, viewed through a small telescope, is a spectacular sight.

The Moon is new on the 1st at 8:24 P.M. It waxes to first quarter on the 8th at 8:57 P.M. and to full on the 15th at 7:57 P.M. The Moon wanes to last quarter on the 23rd at 5:11 P.M.

Unless otherwise noted, all times are given in eastern standard time.

Dolls in the Discovery Room

As a child holds a small doll dressed in a green sari, her parents excitedly point to Bangladesh on a map on the wall nearby, explaining that this is the place her family came from. The child in turn shows her friend.

This is the type of interaction that Ann Prewitt, Discovery Room Director, had hoped for when she thought of using dolls for a small exhibit in the anthropology section of the Discovery Room, a learning space that introduces young visitors to the science of the Museum. Displays, interactive elements, and resource materials engage children in activities about the process of science and expose them to artifacts of other cultures.

This exhibit, like everything in the Discovery Room, not only captivates children, but creates an opportunity for intergenerational learning. It draws in children, their parents, and even their grandparents, who can all relate to something on the shelves and learn more as they discuss and share stories.

The exhibit displays dolls from all over the world along with ones you might find long-forgotten in your own attic. Highlights include:

- **One Hundred Years of American Dolls**, which includes a selection of popular dolls from the 20th century. Each doll, from the original G.I. Joe to Shirley Temple, is accompanied by historical notes along with the owner's personal story.
- **When Is a Doll More Than a Plaything?** is a section that investigates varying meanings of dolls across cultures, such as the Hopi Katsina doll, which is thought to bring spiritual blessings to its owner.
- **Dolls from around the World**, a colorful array of souvenir dolls collected from more than 25 countries. A "postcard" attached to each explains how national and cultural pride informs the look of each doll, whether in modern or traditional garb. An interactive map provides a geography lesson, allowing children and their caregivers to locate and mark the country from which each doll originates.

R. MICKENS/AMNH

Souvenir dolls from around the world

To learn more about this and other activities in the Discovery Room, visit www.amnh.org.

The Discovery Room was made possible by a grant from the Edward John Noble Foundation. Additional support has been provided by former City Council Member Ronnie M. Eldredge, and Mortimer B. Zuckerman.

D. FINNIN/AMNH

The Bison and Pronghorn diorama in the Hall of North American Mammals is the first in a series of virtual versions of the Museum's famous dioramas that will serve as a companion Web site to the forthcoming book due out this February, *Windows on Nature: The Great Habitat Dioramas of the American Museum of Natural History* (Abrams, 2006). Visit http://www.amnh.org/exhibitions/dioramas/bison/ for a 360° view of the diorama and the hall, close-ups and descriptions of individual elements of the diorama, historical notes on the artists and artistry, presentations by curators, and much more.

Darwin

November 19, 2005–May 29, 2006
Gallery 3, third floor

On Saturday, November 19, 2005, the American Museum of Natural History will open *Darwin*, the most in-depth exhibition ever presented on this highly original thinker, botanist, geologist, and naturalist and his theory of evolution.

The comprehensive, engaging exhibition will explore the life and times of Charles Darwin, whose observations and insights in the 19th century forever changed the perception of the origin of our own species as well as the myriad other species on this planet and launched modern biological science.

Visitors will experience the wonders Darwin witnessed on his journey aboard the HMS *Beagle* on its historic five-year voyage (1831–1836) to the Galápagos Islands and beyond: the exhibition will feature live Galápagos tortoises and an iguana and horned frogs from South America, along with actual fossil specimens collected by Darwin and the magnifying glass he may have used to examine them.

The Museum has elaborately re-created Darwin's study at Down House, his rural home outside London, where he proposed the scientific theory that all life evolves according to the mechanism of natural selection. The objects on display, coupled with illuminating text, will provide a clear understanding of the patterns he observed among species, which led to his life's work and the publication of the brilliant and seminal *The Origin of Species*.

The American Museum of Natural History gratefully acknowledges **The Howard Phipps Foundation** for its leadership support.
Significant support for *Darwin* has also been provided by the Austin Hearst Foundation, Jack and Susan Rudin, and Rosalind P. Walter.
Additional funding provided by the Carnegie Corporation of New York and Linda K. Jacobs.
Darwin is organized by the American Museum of Natural History, New York, (www.amnh.org), in collaboration with the Museum of Science, Boston; The Field Museum, Chicago; the Royal Ontario Museum, Toronto, Canada; and the Natural History Museum, London, England.

S. QUINN/AMNH

Blue-footed boobies of the Galápagos Islands

ZHOA JIHUA (65-YEAR-OLD BAI WOMAN), SANSHE VILLAGE/PHOTOVOICE

On view now through March 12, 2006, *Voices from South of the Clouds* is an exhibition of stunning photographs taken by the indigenous peoples of China's Yunnan Province.

PEOPLE AT THE AMNH

Kevin Orangers
Moveable Museum Program Manager
Department of Education

D. FINNIN/AMNH

For ten years, Kevin Orangers has filled a unique and challenging role as an educator, planner, and administrator for the Moveable Museums, an educational outreach program that brings the science of the Museum into the community in retrofitted recreational vehicles. The fleet currently includes *Paleontology of Dinosaurs*, *Structures and Culture* (anthropology), and *Discovering the Universe* (astronomy), and a fourth, on current technology in dinosaur research, is on the way. Each vehicle visits three to four classrooms every school day, with up to 200 kids learning from an in-class introduction followed by an interactive tour onboard the Moveable.

Kevin works on everything from the design of each new exhibition to the development of teachers' resource guides. While his degree in physical anthropology plays a role in conceptualizing the exhibitions, his instinct as a mechanic has also proved invaluable in keeping the Moveables on the road. When he's not tending to the Museum's vehicles, he is toiling over a 1950 Harley Davidson Panhead that lays in pieces, waiting for fabrication and reassembly.

In addition to the technical challenges and excitement of literally creating an exhibition-to-go, Kevin admits that the best part of the job is working in the classroom. "The response you get from the kids all over the city—that's the part of the job that makes you want to come to work every day."

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Darwin

Opens November 19, 2005

A comprehensive, engaging exploration of the life and times of Charles Darwin, featuring live animals from the Galápagos Islands, actual fossil specimens collected by Darwin, archival documents, and more.

The American Museum of Natural History gratefully acknowledges **The Howard Phipps Foundation** for its leadership support.
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Darwin is organized by the American Museum of Natural History, New York, (www.amnh.org), in collaboration with the Museum of Science, Boston; The Field Museum, Chicago; the Royal Ontario Museum, Toronto, Canada; and the Natural History Museum, London, England.

The Butterfly Conservatory: Tropical Butterflies Alive in Winter

Through May 29, 2006

A return engagement of this popular exhibition includes 400–500 live, free-flying tropical butterflies in an enclosed habitat that approximates their natural environment.

Dinosaurs: Ancient Fossils, New Discoveries

Through January 8, 2006

Discover the most current thinking on the mysteries of dinosaurs: what they looked like, how they behaved, and why—or even whether—they became extinct.

Dinosaurs: Ancient Fossils, New Discoveries and its accompanying education and public programs are made possible by **Bank of America.**

This exhibition is organized by the American Museum of Natural History, New York (www.amnh.org), in collaboration with the Houston Museum of Natural Science; California Academy of Sciences, San Francisco; The Field Museum, Chicago; and North Carolina Museum of Natural Sciences, Raleigh.
Major funding has also been provided by the Lila Wallace-Reader's Digest Endowment Fund.

Voices from South of the Clouds

Through March 12, 2006

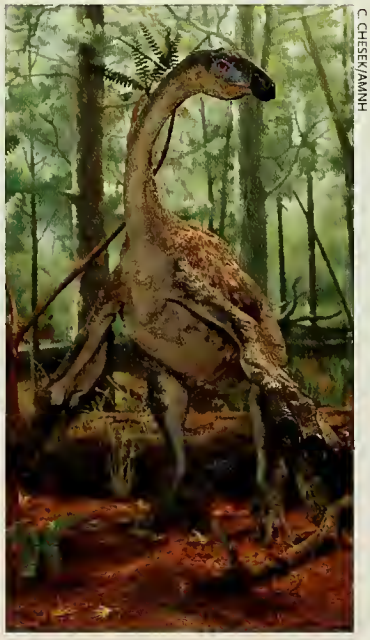
China's Yunnan Province is revealed through the eyes of the indigenous people who use photography to chronicle their culture, environment, and daily life.

The exhibition is made possible by a generous grant from Eastman Kodak Company. The presentation of this exhibition at the American Museum of Natural History is made possible by the generosity of the Arthur Ross Foundation.

Vital Variety

Ongoing

Beautiful close-up photographs highlight the importance of the immense diversity of invertebrates.



C. CHESEK/AMNH

Beipaosaurus model in *Dinosaurs*

MARGARET MEAD FILM & VIDEO FESTIVAL

Thursday–Sunday, 11/3–6, and Saturday and Sunday, 11/12 and 13

The 29th annual film and video festival, showcasing the best international documentaries, will include screenings, discussions, and panels. Visit www.amnh.org/mead or call 212-769-5305 for a complete schedule.

This festival is made possible with public funds from the New York State Council on the Arts, a state agency. NYSCA

LECTURES

Dinosaurs on Film

Saturday, 11/5, 12:00 noon

How have dinosaurs been represented on film? Enjoy clips from classic animation and science fiction blockbusters with John Canemaker of New York University and Carl Mehling, AMNH.

Beyond Oil: The View from Hubbert's Peak

Thursday, 11/17, 7:00 p.m.

Kenneth S. Deffeyes predicts that world oil production could peak as soon as this Thanksgiving. He discusses the ramifications. A book signing will follow.

In Conversation with Alan Lightman

Tuesday, 11/22, 7:00 p.m.

Author Alan Lightman and NPR's Ira Flatow discuss Lightman's new book, *The Discoveries*, in which he reveals the stories behind some of 20th-century science's great moments. A book signing will follow.

FAMILY & CHILDREN'S PROGRAMS

Dr. Nebula's Laboratory: Dino Adventure

Sunday, 11/20, 2:00–3:00 p.m.

Join Scooter for a paleontological dig right in Dr. Nebula's laboratory, where she'll uncover the mysteries of dinosaurs and what might have happened to them.

Space Explorers: Stars and Light

Tuesday, 11/15, 4:30–5:30 p.m.
(Ages 10 and up)

Begin the evening with a hands-on activity designed to prepare you for an in-depth lecture under the stars of the Hayden Planetarium.

Stories of the Sky

Saturday, 11/5
11:00 a.m.–12:30 p.m.

Take a trip into Starlab, a fun, inflatable planetarium,

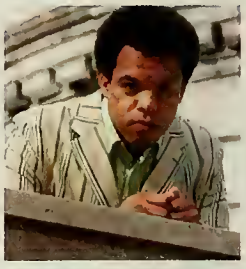
STARRY NIGHTS

Live Jazz

ROSE CENTER FOR EARTH AND SPACE

Friday, November 4

Eric Lewis Groove



Enjoy jazz and tapas on the first Friday of every month.

Starry Nights is made possible, in part, by Constellation NewEnergy and Fidelity Investments.

and use music, games, and storytelling to learn the ancient tales of the Sun, Moon, and stars.

Robots in Space I (For Beginners)
Three Wednesdays, 11/2–11/16, 4:00–5:30 p.m. (Ages 8–10)
Discover how we use robotic rovers and probes to explore places in space where humans are not able to survive. In this class, you will design and build robots using the Lego Mindstorm design system.

HAYDEN PLANETARIUM PROGRAMS

TUESDAYS IN THE DOME

Virtual Universe
Solar System Spectacular
Tuesday, 11/15, 6:30–7:30 p.m.

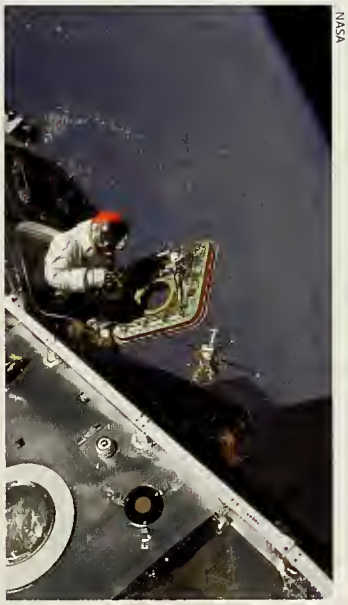
This Just In...
November's Hot Topics
Tuesday, 11/15, 6:30–7:30 p.m.

Celestial Highlights
Sea of Stars
Tuesday, 11/29, 6:30–7:30 p.m.

LECTURE
Frontiers in Astrophysics
Monday, 11/7, 7:30 p.m.

Miss Leavitt's Stars
Monday, 11/21, 7:30 p.m.
With George Johnson, science writer

COURSES
Which End is Up? Telescopes for beginners
Four Mondays, 11/7–11/28 10:00 a.m.–5:00 p.m.


NASA

Apollo 9 astronaut Dave Scott

HAYDEN PLANETARIUM SHOWS

SonicVision
Fridays and Saturdays, 7:30, 8:30, and 9:30 p.m.
Hypnotic visuals and rhythms take viewers on a ride through fantastical dreamspace.

SonicVision is made possible by generous sponsorship and technology support from Sun Microsystems, Inc.

The Search for Life: Are We Alone?
Narrated by Harrison Ford

Made possible through the generous support of Swiss Re.

Passport to the Universe
Narrated by Tom Hanks

LARGE-FORMAT FILMS

LeFrak IMAX Theater
For films and showtimes, visit www.amnh.org or call 212-769-5100.

IMAX films at the Museum are made possible by Con Edison.

NASA, STSCI

The Quintuplet Cluster

INFORMATION

Call 212-769-5100 or visit www.amnh.org.

TICKETS AND REGISTRATION

Call 212-769-5200, Monday–Friday, 9:00 a.m.–5:00 p.m., or visit www.amnh.org. A service charge may apply. All programs are subject to change.

AMNH eNotes delivers the latest information on Museum programs and events to you monthly via email. Visit www.amnh.org to sign up today!

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Patterns

By Niles Eldredge

When I set out to organize the "Darwin" exhibition, as part of the American Museum of Natural History's great scientists series—and as an early start on Darwin's birthday celebration in 2009—I began with a simple question: What exactly did Darwin see on his famous voyage around the world (1831–36) that led him to his theory of evolution?

The answer to this question is "patterns." Darwin saw patterns in nature that cried out for explanation. In South America, he discovered the bony plates of glyptodonts—creatures reminiscent of armadillos, but much larger—and (at a separate site) the fossil bones of giant ground sloths. South America was also home to living species of armadillos and sloths. Why would fossil remains and modern species found on the same continent resemble each other?

His second observation was the pattern of distribution of some living species in South America. He saw the common rhea—an ostrichlike bird—living in Argentina. Then he found a smaller Argentinean species living farther south, its range just barely overlapping that of the larger bird. Why do those flightless birds, unique to South America, seem to replace each other in adjoining regions?

A third pattern Darwin noted was that distinct forms of otherwise similar animals occur on the various islands of the Galápagos archipelago. He observed several unique species of mockingbirds on the islands, and surmised that they must all be related to the mockingbirds of mainland South America, 600 ocean miles away. (He noted the pattern of the famous finches only after he returned to London and an ornithologist called it to his attention.) Darwin also learned that locals could tell from which islands giant tortoises had come by the shapes of the reptiles' shells. While still aboard the *Beagle*, he speculated about whether similar patterns of distribution might hold in other island groups. If so, he noted, it would tend to "undermine the stability of Species"—the earliest hint of the idea of evolution in his writings.

I believe that by the time he returned to England, Darwin had become a confirmed evolutionist. He was now speculating not about whether species had evolved, but how. Departing from his plan to compile additional examples of his original three patterns, he looked for other patterns that would make sense if evolution was true.

Darwin reexamined one pattern that was well known to the naturalists of his day: the Linnaean system for classifying plants and animals, in which sets of species are nested within ever-larger groupings. In his Notebook B, Darwin sketched out a branching tree of species [*see illustration on page 64*], adding in a note that the nearest branches (closest relatives) would resemble each other more closely than they would their remote relatives. Darwin realized that Linnaeus's hierarchical system could be viewed not merely as groupings of similar types, but as patterns of evolutionary relationships and descent.

Of the three patterns he observed during his *Beagle* voyage, Darwin arrived at a fully satisfactory explanation for one: the Galápagos birds and tortoises evolved according to local conditions when they were isolated for long periods on the islands of the archipelago. But he had difficulty imagining how isolation could operate on vast open stretches of continents. His attempt to explain divergence by natural selection in the case of such species as the two rheas was intriguing but incomplete. Evolutionary biologists now understand that past climatic and geologic changes have often created barriers that split up populations. When those physical obstacles later disappear, the two related species may once more share the same ranges. As for South America's extinct and living sloths and armadillos, Darwin correctly concluded that they were related, but was uncomfortable with the fossil evidence, which did not fit his view of gradual evolution through natural selection.

Darwin's theory has itself evolved over the years. Yet it is worth recalling that modern evolutionary biology was founded when a young naturalist—a creationist at the time—was struck by three puzzling patterns in nature. To him, the patterns all pointed toward a single, great truth. "I cannot possibly believe," Darwin wrote in 1859, "that a false theory would explain so many classes of facts." □

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—Frans Lanting, photographer-in-residence, National Geographic Society and author of Jungles *and* Eye to Eye

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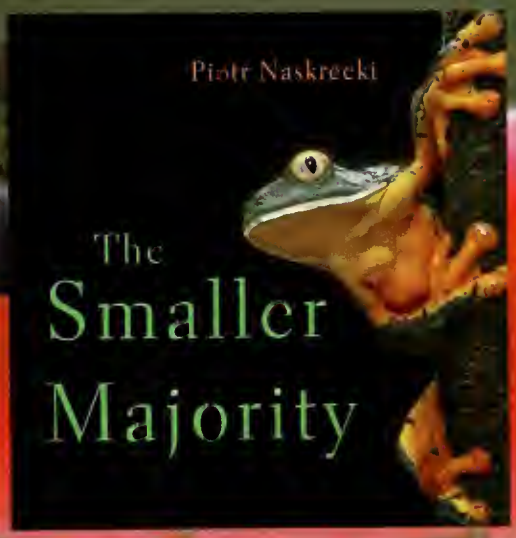

Large photograph: Leaf katydid (*Hyperphrona irregularis*) (Costa Rica) Copyright (c) Piotr Naskrecki

"If I were to name one group of organisms that encapsulates everything I love about nature, it would be katydids. They behave in intriguing ways, and their physical beauty is matched by their captivating songs." —from the book

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