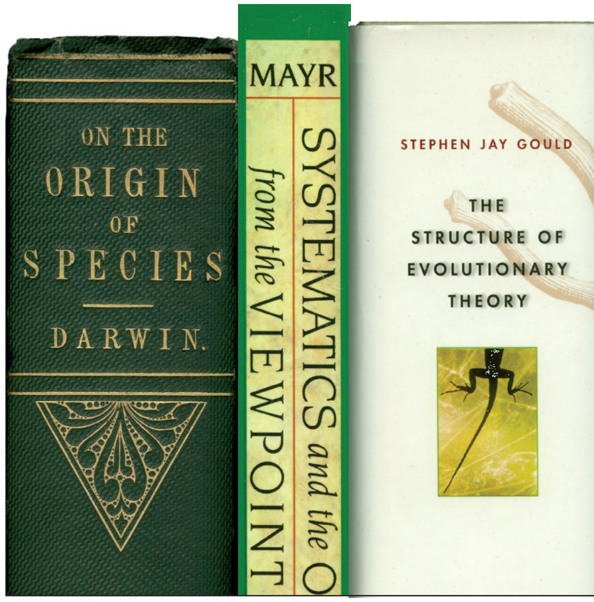
Evolution's Evolution

Darwin's dangerous idea has adapted to modern biology By Rachel Ehrenberg



Just a decade after he published *On the Origin of Species,* Charles Darwin was already worrying about the evolution of his idea. In an 1869 letter to botanist Joseph Dalton Hooker, Darwin lamented: "If I lived twenty more years and was able to work, how I should have to modify the *Origin,* and how much the views on all points will have to be modified! Well, it is a beginning, and that is something."

Calling the *Origin* a mere "beginning" is like saying the Beatles were just a rock band or that Shakespeare wrote some decent plays. Darwin's gifts to science were radical. He not only proposed that all of Earth's diverse beings shared a common ancestry, but also described an elegant mechanism to explain how all that diverse life came to be. Darwin was a master of merging data from different disciplines, painstakingly drawing from zoology, botany, geology and paleontology to build a solid foundation for evolutionary biology. Today, 150 years later, scientists continue to grapple with ideas descended from that foundation. Still, Darwin's central tenets survive, fit enough to frame the questions posed by modern biology.

"He had great intuition," says Yale University's Michael Donoghue. "He's the guy we all envy."

Darwin's powers of observation and reason extended from microflora to megafauna; he could see the whole forest while scrutinizing the branches on the trees. His ideas illuminated life's development in the Earth's deep past and foreshadowed many scientific developments that would come in the future, including the modifications and refinements to his theory that scientists are still exploring. Yet, were Darwin alive today, his head might spin at the complexities entangling the expansion of his original ideas.

Evolutionary theory is not a well-preserved fossil in a dusty museum, but a thriving field of study pursued at lab benches, on beaches and in bogs. The exploding research program known as "evo-devo," for instance, has wed evolutionary theory to embryology and genetics, helping to unravel the evolution of organisms' structures and forms. Scientists are also reformulating ideas about evolution's pace, showing that Darwin's idea that change happens gradually and incrementally doesn't always capture the whole story. Researchers are fleshing out Darwin's central idea of natural selection — discovering when it's the driver and when it takes a back seat. And along with investigating how selection operates on organisms — Darwin's unit of choice — scientists are also showing how it acts on groups, genes and behavior. Experts are still debating the very definition of a species.

If Darwin came back, "in some ways he would be mystified," says evolutionary biologist Douglas Futuyma of Stony Brook University in New York. "Evolutionary biology has been radically changed — and deeply enriched."

The 'dangerous idea'

Of course, Darwin was familiar with radical change. In his day most biologists (or "naturalists," then) believed that each species was individually created and forever immutable. But during his travels in the 1830s on her majesty's ship the *Beagle,* Darwin saw plants and animals and fossils — and distributions of all three — that just didn't square with the idea that species don't change.

"It was evident that such facts as these, as well as many

65 mya
Asteroid hits Earth. Mass extinctions of marine life and some terrestrial life, including dinosaurs (ancestors of modern birds). The age of mammals begins.

65 to 1.8 mya
(Tertiary period)
Birds, mammals, insects and flowering plants are widespread and flourish.

25 mya
Establishment of present-day forests; climatic cooling and restriction of broad-leaved evergreens to lower latitudes; prairie grasses

REPRODUCED WITH PERMISSION FROM JOHN VAN WYHE, ED., THE COMPLETE WORK OF CHARLES DARWIN ONLINE (DARWIN-ONLINE.ORG.UK); TIMELINE: PUBLIPHOTO/PHOTO RESEARCHERS (BOTH) others, could only be explained on the supposition that species gradually become modified; and the subject haunted me," he noted in his autobiography.

Upon his return to England, Darwin pored over his notes and "collected facts." Eventually he accepted the unacceptable and wrote, in 1844, to his friend Hooker: "At last gleams of light have come and I am almost convinced (quite contrary to the opinion I started with) that species are not (it is like confessing a murder) immutable."

That year Darwin penned his idea in a manuscript that remained unknown to the public until portions of it were presented to the Linnean Society in 1858. Subversive as it was, Darwin's proposal that species can change was not the first. Naturalists and philosophers had long been contemplating life's diversity. By the late 1700s, French naturalist Georges Cuvier had established that after great environmental change, some organisms got snuffed out, went kaput, extinct. A little later, zoologist and philosopher Jean Baptiste Lamarck proposed the notion of adaptation, explaining variation among organisms as a response to their environments. But Lamarck saw the change in organisms through time as a one-way path to perfection, from simple to increasingly complex, with humans at the pinnacle. His environment-caused variation was an excuse to explain why some organisms strayed from the "tendency toward perfection."

It took Darwin and Alfred Russel Wallace to recognize (independently) that variety was actually the spice of life, not its flaw. Both men had read the work of economist Thomas Malthus, who warned that food supplies could never keep up with growing populations. No matter what, some people would meet an early death. Darwin and Wallace both reasoned that beetles, birds and beech trees also have more babies than can survive and that variation among such offspring was important in determining who lived. Individuals who were better equipped for their environment than their siblings or neighbors would survive; the features that enabled their survival would be passed on to their kids.

Darwin called this process natural selection, and life evolved largely because of it, he argued in the *Origin*. (The word *evolved* appeared only once, the last word on the *Origin*'s last page: "from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.") Evolution via natural selection, Darwin believed, could yield both life's incredible diversity and its striking similarities.

Those similarities are repeatedly and presciently remarked


Porpoise paddle


Mole


Human hand

"What can be more curious that the hand of a man, formed for grasping, that of a mole for digging, the leg of a horse, the paddle of the porpoise, and the wing of the bat, should all be constructed on the same pattern, and should include the same bones, in the same relative positions?"

— Darwin, *On the Origin of Species*

CLOCKWISE FROM BOTTOM LEFT: ANDREAS FEININGER/TIME & LIFE PICTURES/GETTY IMAGES; PHILIP DOWELL (C) DORLING KINDERSLEY; ROBERT CLARK; TIMELINE: PASCAL GOETGHELUCK/PHOTORESEARCHERS; PHILIPPE PLAILLY & ATELIER DAYNES/PHOTO RESEARCHERS

20 mya
Proconsul, one of the earliest apes, appears around this time.

5.3 to 1.8 mya
(Pliocene epoch)
The likely human ancestor *Australopithecus* lives at various African sites. The famous partial skeleton "Lucy" is thought to be from 3.2 million years ago.


A model of "Lucy"

2.5 to 2 mya
The first species of the genus *Homo* lives in southern and East Africa.

upon by Darwin, who called morphology — the study of form — “the most interesting department of natural history, and may be said to be its very soul.” In the *Origin* he writes: “What can be more curious that the hand of a man, formed for grasping, that of a mole for digging, the leg of a horse, the paddle of the porpoise, and the wing of the bat, should all be constructed on the same pattern, and should include the same bones, in the same relative positions?”

But only in recent years have evolution and embryology become integrated into a flourishing field dubbed “evo-devo,” for evolutionary development, a research program investigating how bodies — their size, shape, color and different parts — evolve.

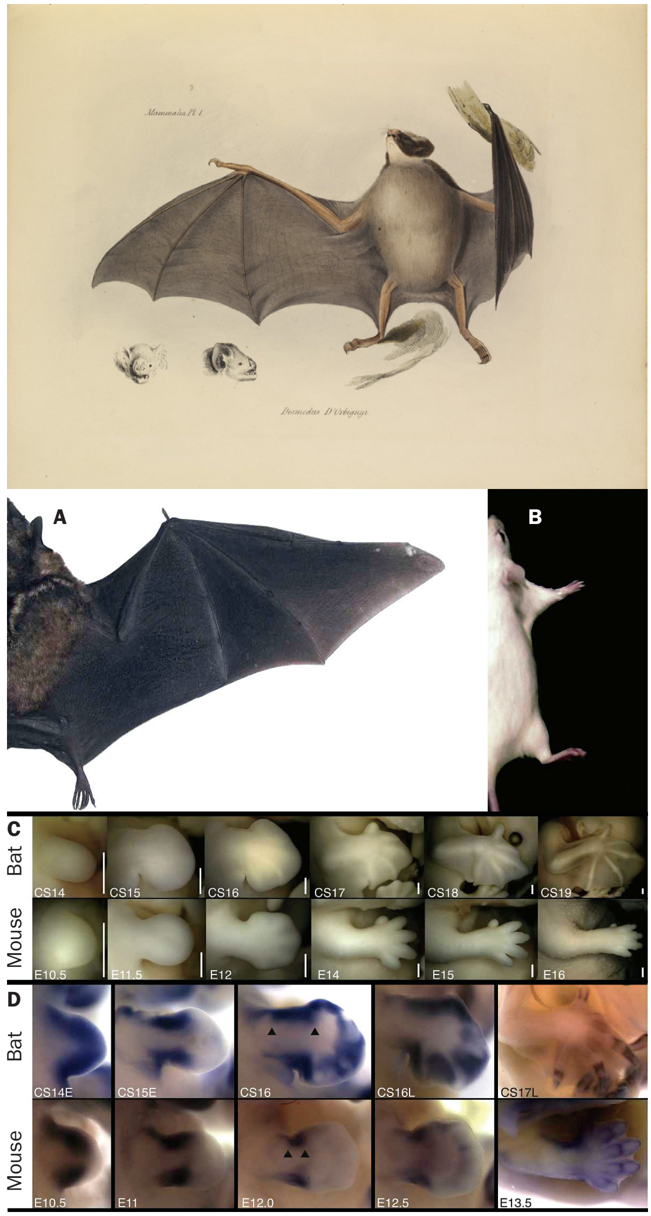
Body building

An early evo-devo milestone came in the 1980s when scientists learned that the genes for the body plan in fruit flies have counterparts in creatures as distantly related as humans, worms and yeast. As opposed to housekeeping genes that code for proteins involved in day-to-day living, these toolkit genes actually govern the construction of the house. Mutations in some fruit fly toolkit genes, for instance, transform a fly’s antennae into legs.

Scientists are finding more and more cases where toolkit proteins do the same jobs in animals separated by many millions of years of evolution. The toolkit proteins in charge of building the contractile muscles that eventually become a pumping heart, for example, appear to be shared by flies and fish and even mammals.

Mining the DNA record has revealed that regulation of gene activity — often by stretches of DNA previously thought of as junk — is critical in shaping development. These regulatory regions of DNA command genes to roar, keep quiet or merely murmur — making lots, none or a little of the molecules they encode. Several plant traits that aided domestication are associated with changes in where, when and how much genes are turned on. Mutations in genes linked to this regulation process helped enlarge tomato’s fruit, for example. Changes in regulation also get credit for the architectural shift from corn’s shrubby progenitor to the single-stalk version that now grows as high as an elephant’s eye.

While DNA is the ultimate forensic record of evolution, it hasn’t closed the case of how organisms develop. Scientists are still debating the precise role of regulatory DNA in large-scale morphological changes, but evidence is accumulating that the timing and location of gene regulation are as impor-



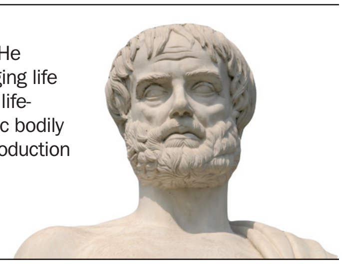
Going batty
Darwin sought intermediates that would shed light on the evolution of novelties such as bat wings (top). By comparing development in related animals (C), scientists are closer to understanding how novelties arise. Tracking a gene linked to limb development (shown in blue) reveals cranked up activity in the developing bat limb (D). And when that piece of DNA was taken from a fruit bat (A) and stuck in a mouse (B), the mouse’s limb length increased significantly, scientists reported last year.

1.8 mya
Homo erectus lives in East Africa and eventually spreads throughout Africa and to Europe and Asia.

150,000 to 100,000 years ago
Appearance of first *Homo sapiens,* who migrate across Africa and Europe

100,000 to 40,000 years ago
Homo neanderthalensis, now extinct, lives in Europe and Asia.

384 to 322 B.C.
Aristotle’s lifetime. He defines an unchanging life hierarchy based on life-forms’ characteristic bodily activities, from reproduction to reasoning.



tant as changes in good old-fashioned protein-coding genes.

DNA also allows scientists to penetrate the smokescreen often presented by anatomy. Many cave-dwelling fish, for example, which spend their lives in perpetual darkness, have lost their eyes and pigment, which puzzled Darwin (he ascribed the fishes' loss of eyes as "wholly to disuse"). But scientists have recently shown that the loss results from the careful coordination of gene activity — the eyes are actively "killed" during development. Why remains unknown.

Exploring the gulf between genes and an organism's observable physical and biochemical traits (its phenotype) has revealed a much more complex picture of selection and inheritance than sketched by Darwin. In his view, natural selection was a grim reaper whose scythe was the external environment. As the late paleontologist Stephen Jay Gould put it, the organism proposes, the environment disposes. But many scientists now view the developing body as an environment in constant conversation with itself. Rather than a one-way street from DNA to organism, scientists now talk about U-turns, crosstown buses and roundabouts.

"It's much more complicated than what we thought," says biologist and philosopher Massimo Pigliucci of Stony Brook University. "Nonlinear interactions, branching, with lots of feedback. That's the new frontier."

"Nonlinear interactions, branching, with lots of feedback. That's the new frontier."
Massimo Pigliucci
Stony Brook University

For example, more and more scientists are investigating how environmental factors such as pH, diet or nurturing behaviors can change the way DNA is packaged. This packaging, which involves such features as the presence or absence of a chemical tag, can change gene activity, and these epigenetic patterns can be inherited. Such findings suggest "a bewildering increase in the complexity of the entire inheritance system," Pigliucci wrote recently in *Evolution*.

Other factors influencing the evolution of shapes and forms include the physical properties of cells.

"Take a pool of water — we're familiar with it having a still surface," says Stuart Newman of New York Medical College in Valhalla. "If we agitate it, we can get waves or vortices — but it can't do any old thing. It's hard to get variety — there's only a few things it will do based on its physical properties."

Similarly, the clusters of cells in a rudimentary embryo can do only so much. One kind of perturbation might make them elongate, another might prompt a hollow cavity to form. Newman and his colleagues reported last year in *Developmental Biology* that when wings and legs begin to bud off a developing chicken embryo, a protein spurs the limb cells to become more cohesive than nearby nonlimb cells. This physical property of being differentially sticky can lead to the layers of tissues seen in embryos. Add some feedback loops and you can get repeating patterns, the kinds of patterns seen over and over again in animal body plans, such as the vertebrae of a backbone or a segmented abdomen.

Of course, even if physical properties can dictate some limits on form, you also need selection, says Newman. "There's still going to be a shakeout — you need selection on what can exist." But physics may have had much more to do with the evolution of innovations — the big leaps on the path of life — than Darwin had realized.

"Darwin wanted a worm to be an incremental worm, to build up little by little. But you don't have to put waves in the water one by one. If you use physics you can get segments in one generation with a feedback loop," Newman says. "You can get rapid transitions to novel forms with physics."

Not always gradual

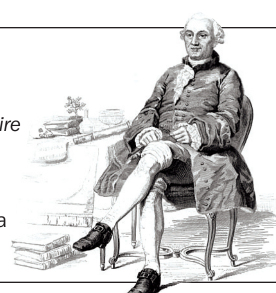
Darwin was not a fan of rapid transitions. In his view evolution acted through the relentless accumulation of tiny changes through vast spans of time. These gradual transitions are sometimes found in the fossil record, but plenty of times they are not. And that record also reveals exuberant bursts of innovation, such as the Cambrian explosion, a period of roughly 20 million years beginning about 520 million years ago. The major body plans found in most modern animal groups, such as arthropods and chordates, were established by the Cambrian, available fossil evidence suggests.

In 1971 Niles Eldredge proposed an explanation for these moments of great change, an idea he later expanded with Gould. Rather than evolution always proceeding as an "easy and inevitable result of mere existence, as something that unfolds in a natural and orderly fashion," Eldredge and Gould argued that it can happen in fits and starts. Organisms remaining unchanged for long periods of geologic time — the

1651
William Harvey publishes *On the Generation of Animals*, which describes how the embryo is built, pioneering modern embryology. Harvey also argues that all animals emerge from an egg.

1745
The work of Pierre-Louis Moreau de Maupertuis hints at the idea of natural selection.

1749
Georges-Louis Leclerc, Comte de Buffon (right) begins publishing *Histoire Naturelle*. It notes similarities between humans and apes and that the two may have a common ancestor.



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1753
In *Species Plantarum*, Carolus Linnaeus classifies plants according to a binomial system of genus and species. He later does the same for animals.

stability so often seen in the fossil record — was actually the norm. This general state of equilibrium is then on occasion punctuated by the emergence of new species.

Punctuated equilibrium (or punk-eke) considered the limited clues left at the geologic crime scene. Say you are a paleontologist and observe the same snail fossil in layer after layer of rock. Then in the next layer up, a different snail fossil appears. What went down? Darwin's gradualism can't be excluded; the rock layers represent millions of years and Snail One might have gradually changed into Snail Two, but the transitional snails never fossilized.

Not necessarily, though. Say a barrier, such as a river, isolated a portion of the snail population. This smaller population might undergo intense selection quickly (in geologic time, where 5,000 to 10,000 years is a blink), becoming a new species. If the river then dries up, the new species is reunited with its sister species. The new species could outcompete its sister, which goes extinct, or both snail species might persist. In the fossil record, it might look like one species was replaced by a related species, or that a new species suddenly appeared.

Eldredge and Gould were familiar with the work of biologist Ernst Mayr and geneticist Theodosius Dobzhansky, who developed ideas on how species originate, laid out in Mayr's 1942 book *Systematics and the Origin of Species*. Punctuated equilibrium captured Mayr's idea of speciation — an isolated subpopulation accruing so many changes that it can no longer breed with its former population — and translated it into the language of the geologic record.

Mayr's ideas became a core part of the "modern synthesis," the merging of Darwinian selection with Mendelian genetics and paleontology during the 1920s through the 1940s. In the early 1900s, after the rediscovery of Mendel's pea experiments, scientists such as Thomas Hunt Morgan began experimenting with fruit flies and established that mutations could be passed along to the next generation. The 1920s brought scientists such as J.B.S. Haldane, Ronald Fisher and Sewall Wright, who gave evolution a mathematical backbone. The field of population genetics was born; its tenets being that variation arises in populations through both random genetic mutation and recombination (sex), and evolution occurs when the gene frequencies in a population change through time. Dobzhansky's and Mayr's ideas on speciation rounded out the mix, laying a rich foundation for exploring how evolution proceeds.

Selection and chance

While adaptation was at the core of the modern synthesis, the mathematical musings of Fisher and Wright demonstrated that natural selection wasn't the only guest at evolution's cocktail hour. Chance also plays a role in determining the genes of the next generation.

The idea of natural selection "was brilliant, original, it was called the 'dangerous idea' because it was so powerful," says Futuyma. "But is that going to explain everything? No."

> The idea of natural selection was "called the 'dangerous idea' because it was so powerful."
>
> Douglas Futuyma
> Stony Brook University

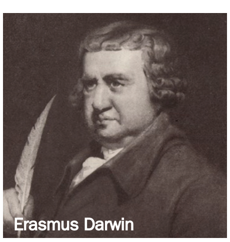
Recall the snail population that gets divided by a river and suppose that the original population was a mixture of red-shelled snails and brown-shelled snails. When the river runs through it and isolates a portion of the population, that new subpopulation — just by chance — might be mostly red snails.

Through time, the genes for red shells might dominate in this new population, or they might peter out — the ratio of brown to red snails will "drift" around. This genetic drift happens without selection — neither color gives either snail a leg up in that environment — yet the gene frequencies for different shell colors in the population are changing through time. That genetic drift — often called the evolutionary equivalent of statistical sampling error — can be a mechanism of evolution. Drift can also reduce the amount of variation in a population, especially if that population is small, leaving natural selection less raw material on which to act.

While the idea of genetic drift arose out of the math of the modern synthesis, it was largely seen as a sideshow to selection's starring role. But following the discovery in 1953 of DNA's structure, molecules grabbed the attention of many scientists; intense investigations of enzymes, other proteins and amino acids, protein building blocks, ensued. In the late 1960s geneticist Motoo Kimura and others began making the case that most changes at the molecular level were neutral — imparting no benefit, or harm — suggesting that genetic drift, not selection, was the prevailing evolutionary force.

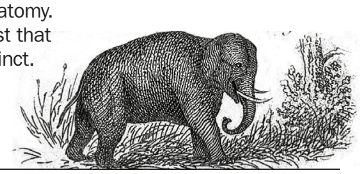
Many scientists found Kimura's "neutral theory" tough to

1794
Charles Darwin's grandfather Erasmus Darwin writes that "warm-blooded animals have arisen from one living filament … possessing the faculty of continuing to improve by its own inherent activity."


Erasmus Darwin

1795
James Hutton proposes the theory of geological uniformitarianism.

1798
Georges Cuvier publishes studies of mammoth and Indian elephant anatomy. His findings suggest that species can go extinct.



swallow, seeing it as relegating selection to the sidelines. But today scientists generally accept that the evolution of molecules may differ in some ways from the evolution of organisms. Selection is still a star, drift certainly has its place, and which has the dominant role is often a matter of circumstance and which level of the hierarchy is being examined.

Acknowledging mechanisms other than selection didn't minimize Darwin's contribution; rather it signaled a larger view of evolution. This refreshing breadth vitalizes many subspheres of evolutionary theory, including the question of where in the biological hierarchy that selection really does its business.

Russian nesting dolls

Darwin doggedly argued that selection acts on organisms, each individual engaged in a personal struggle for survival. Troubled by the sterile workers of a bee colony, he fumbled to explain how their existence did not "annihilate" his whole theory. Investigating "the" target of selection is still a productive if contentious field, but increasingly scientists are embracing a hierarchical view. Evolution can be a team sport, with selection acting above the level of individual, for the "good of the group." Selection can also act below the level of the organism — on genes and cells.

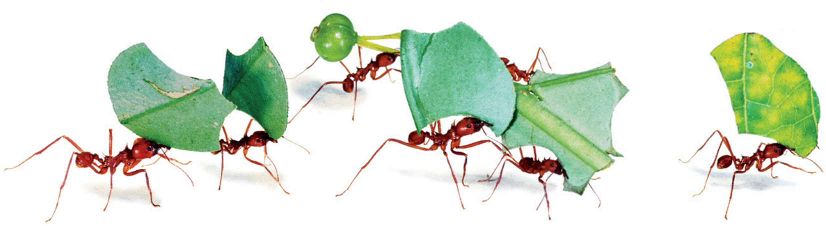
Sterile workers of a bee or termite nest who live in dedicated service to their queen, or a vampire bat who regurgitates blood for colony members who haven't had a meal, are examples of altruism — their behavior benefits other organisms, often at a cost. In the Darwinian, organism-focused view, altruism shouldn't evolve. But if selection can act at the level of groups (an idea broached by Darwin in *The Descent of Man*), a gang of altruists might have an advantage over a gang of selfish individuals.

However, if there is a cost to behaving kindly, then selfish individuals should have an advantage, which would eliminate altruism from the gene pool. In the 1960s, though, scientists started thinking about altruism in terms of kin. If altruistic behavior benefits relatives, then even if an individual doesn't get to pass on its genes, its siblings might. "Kin selection" says that organisms will behave altruistically toward close relatives, a prediction borne out by research, including recent work showing that related male turkeys work together to attract females, even though only the dominant male might sire offspring.

While debate continues over where and how selection acts, many scientists advocate the "Russian nesting doll" approach that allows selection at numerous levels, including species, groups, individuals, cells and, of course, genes, as popularized by British evolutionary biologist Richard Dawkins.

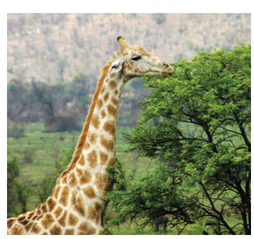
A similarly contentious (and productive) area of research focuses on the concept of "species" itself. Experts still debate whether Darwin concerned himself with actually defining species; many scientists argue that he viewed the category as an arbitrary point in the fuzzy, gradual divergence of lineages. In the past 50 years many species concepts have been proposed. A dominant approach, first championed by Mayr in animals (and later by botanist Verne Grant in plants), argues that

In a leafcutter ant colony the only female who mates is the queen. Scientists now understand that the sterile or celibate lifestyle could still evolve if kin get to pass on genes.

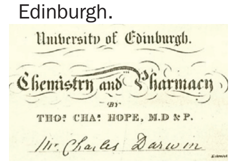


1809
Charles Darwin is born February 12 in Shrewsbury, England.

1809
Jean Baptiste Lamarck states in the *Philosophie Zoologique* that heritable changes could be forged by the environment during an organism's lifetime.



1825
Darwin matriculates at the University of Edinburgh.



species are real entities defined by their ability to interbreed. Yet some organisms snub this "biological species" concept. Among species with several populations over an extended range, it isn't unusual that populations near each other can successfully interbreed, while populations at the opposite ends of the range (or ring) are so divergent that they are incompatible. (Recent work on *Ensatina* salamanders of the Pacific Coast, a noted example of a ring species, indicates both current and past hybridization between some of the more distant "species," complicating matters further.)

While the ability to interbreed is certainly important in the maintenance of species, it does leave something to be desired as a definition (what about asexual species, for example?). Some scientists have proposed phenetic species, which define organisms by their overall similarities. Many scientists now call for a phylogenetic species concept that recognizes groups descended from a common ancestor, as evidenced by the sharing of special derived characteristics, such as mammals having fur and mammary glands. Brent Mishler of the University of California, Berkeley, who with Donoghue was a framer of the phylogenetic species concept, has recently argued that hierarchical ranking, from subspecies to species and up through families and orders, is of little use intellectually or practically and that ranks on all levels, species included, should be done away with.

> "The mighty maze of organic life was no longer without a plan."
>
> Grant Allen, writing in Darwin's obituary

The tree of life has thousands of nested levels, Mishler writes in a chapter to appear in *Contemporary Debates in Philosophy of Biology*. Defining species — or any other rank for that matter — is in many ways arbitrary. For example, given a genus of moths and a genus of spiders, the rank of "genus" actually tells us almost nothing about the two groups, such as their evolutionary age, or the number of species. It would be better to recognize branches or "clades" on the tree of life — a fork and all the twigs that arise from it, which actually have meaning evolutionarily, Mishler says. For a conservation land manager comparing bird diversity in two canyons, for example, the meaningful information is how much of the bird section of the tree of life is represented in each canyon, not how many species.

Mishler points to similar problems with discrete definitions, biological or otherwise. Take the Gulf Stream, for example. It is so distinct that you can see it from outer space. "This water comes up from Florida, crosses the Atlantic, and affects the weather in England — it is absolutely real," Mishler says. "But if you were in a rowboat at the Gulf Stream's edge and were trying to tell me which molecule of water is part of it and which isn't — you'd be hard pressed."

While humans crave discrete definitions, little in biology is tidy, and putting its parts together isn't necessarily becoming easier. In making the tremendous progress since Darwin in documenting and exploring the mechanisms of evolution, scientists have become more and more specialized, says Pigliucci. That's how novel contributions are made. But ironically, that specialization often comes at a cost — there's a lack of integration at higher levels — even though integration was Darwin's claim to fame. His insights connected everything in biology, all life becoming related pieces of an integrated whole.

"Genealogy became the great problem of zoology and botany, of paleontology, and of all allied studies. The mighty maze of organic life was no longer without a plan," scholar and writer Grant Allen wrote in Darwin's obituary in April 1882.

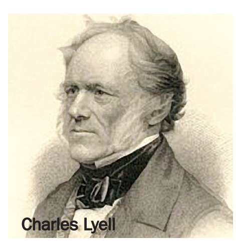
Such integrated thinking is needed today as humans grapple with how ecosystems will respond to climate change or invasive species, says Futuyma. Figuring out the genetic variation in a little alpine weed is one thing, but it doesn't necessarily tell you whether that plant will be able to adapt to a warming world.

"It's funny that evolutionary biology has not played much of a role in biodiversity — it's been almost entirely seen as an ecological issue," says Donoghue. "But evolutionary biology has a lot to say about these issues — oddly enough, evolutionary biology is all about diversity. We're just starting to connect these dots."

Darwin was all about connecting dots, says Pigliucci. "Today Darwin would be excited and bewildered by what we know, but would also probably push us to focus on the interdisciplinary aspects," he says. Darwin was "an inherently interdisciplinary guy. But it took him years! The bulk of the *Origin* is painstaking examples from a variety of disciplines — in a sense we aren't there now. We know a lot about molecular biology and development in model systems and we know a little about ecology and evolution, but we know almost nothing about how they all fit together." ■

1827
Darwin is admitted to Christ's College, University of Cambridge.

1829
Geologist Charles Lyell (right) publishes his *Principles of Geology*, promoting the idea that the surface of the Earth is gradually and continually changing.



1831
Darwin earns his undergraduate degree at Cambridge.