Seven

Dinosaur Feathers

Sometimes I get a little selfish about dinosaur skeletons. As thrilled as I am that museum dinosaur exhibits are so well attended, the stampeding hordes of schoolchildren and waves of parents pushing their stroller-bound kids through narrow exhibit pathways can be more than a little agitating. Walking through dinosaur displays at peak hours requires serious agility to avoid the swarms of little ones buzzing around the place. And that's not to mention the fact that few people seem to read the museum labels—any sharp-toothed predator is a *Tyrannosaurus*, and every supersized sauropod is a "*Brontosaurus*." I want to butt in and point out the correct names, but when I've done so, I have often been met with annoyed glares. Better to keep my mouth shut and let the families enjoy their time in the midst of the fossilized superstars. "Be nice," I have to remind myself, ". . . you're just one of those irrepressible dinosaur fanatics all grown up."

I often watch the tide of visitors go by from the bench at the Natural History Museum of Utah's paleontology lab. Behind a set of high glass windows, the other volunteers, technicians, and I go to work in a scientific fishbowl among tables stacked with fossils and covered in flecks of prehistoric rock. Sometimes I'll be absorbed in my work—breaking off tiny pieces of sandstone from a fossil in the raw—and over the whine of the air-powered scribe I use to pick away at the encasing rock, I'll hear a bang on the windowpane as a gaggle of kids catapults themselves onto the glass to get a better look. They're so excited—until they realize that cleaning dead dinosaurs is a real pain in the ass, a war of millimeters between you and the matrix that surrounds the fossil bone.

On some afternoons, when the flow of museum patrons has ebbed, I take a few minutes to amble through the exhibit halls. The quiet of the vast, dim space reminds me of my first trip to see New York City's grand dinosaurs. The osteological galleries are among the few places where I can tune out the various distractions, always just a tap away on my smartphone, and let my mind drift as I walk past a pack of *Allosaurus* poised on tiptoe and gaze up to the ludicrously long neck of the museum's titanic *Barosaurus*. I feel at home among the dinosaurs.

And in those moments, I can't help but wonder what the animals looked like when they were alive. Dinosaur skeletons are beautiful, exotic frameworks that supported flesh in life, and are the jumping-off point for my daydreams now. Fossil impressions of pebbly dinosaur skin fill in some of the details, but that's just the canvas. Dinosaur color is another matter altogether. I can imagine sloshing buckets of polka-dot paint over the museum's many-horned *Utahceratops*, but I doubt that in reality he would have looked so conspicuous. On the other hand, the traditional garb of drab green or gray isn't very appealing, either. Maybe the horned dinosaur shared a palette with today's African antelope, like the bongo—sienna shades set off with patches of black and thin white stripes. I can always revise the color scheme later.

When I was a kid, books and museum displays told me that dinosaur color was one tantalizing aspect of *Apatosaurus* and company that we'd never be able to find out. The mystery was as frustrating as it was fascinating, and, from what I've heard, "What color were dinosaurs?" is still the question paleontologists field most often. For a long time, there was no answer. Whether working in paint or with the animatronic dinosaurs that terrified me the first time I saw them, artists could have free rein to pick any color scheme they wanted without fear of scientific reprisal.

I used this to my advantage when I was still a young dinosaur fan and created a few dinosaur drawings for the paleontologist Peter Dodson. My father told me he was taking me to Dodson's lecture at the local library, and I couldn't wait. This was my chance to impress a real paleontologist! Someone who could open doors to fantastic collections and fossil-rich field sites! So I spent the afternoon sketching dinosaurs, including what turned out to be an atrocious drawing of the many-horned dinosaur *Styracosaurus*. This dinosaur had the same build as *Triceratops*, but with a vastly different head—a long nasal horn, short brow horns, and an array of intimidating spikes jutting backwards from its frill. And I honored this proud dinosaur by giving it a truly awful color scheme, too. The ceratopsid's beak reminded me of a macaw, so I colored the dinosaur fire-engine red with a splash of white and black around the eye. I started with the eye first, and instantly regretted it. All the same, who could say? Later that night, I presented Dodson with the garish dinosaur. I'm forever grateful that he didn't burst out laughing.

That dinosaurs might have been so fantastically colored was a relatively new idea during my childhood in the 1980s, a concept that grew out of the notion that dinosaurs were more birdlike than anyone ever expected. Before that, dinosaurs traditionally wore stately, subdued colors. Olive green and mud brown were the default choices. Even movie dinosaurs, who were meant to be ferocious, vibrant creatures, had scaly hides duller than a pet-store lizard. The comically carnivorous "*Brontosaurus*" in *King Kong* (as well as the rest of Skull Island's Mesozoic fauna, for that matter) flickered as gray monstrosities in weekend reruns of the film on my family's television set, the grayscale colors a necessity of the early days of cinema. But dinosaurs in the age of color were lackluster, too. Ray Harryhausen's anachronistic *Triceratops* and *Ceratosaurus* in 1966's *One Million Years B.C.* wore uniform shades of brown and gray, and the brontosaur family of *Baby: Secret of the Lost Legend* were solid charcoal. Even *Jurassic Park* (which debuted two decades after artists and scientists took the colorful lessons of the Dinosaur Renaissance to heart) featured typically drab dinosaur stars. Apparently Steven Spielberg wanted classic Hollywood monsters rather than the most accurate dinosaurs science could offer. Jack Horner, who has been a paleontology consultant for blockbuster dinosaur films, once told me that the director drew a hard line on what the dinosaurs should look like, noting that Spielberg felt he couldn't "scare people with Technicolor dinosaurs."

By the time *Jurassic Park* came out, the dull dinosaurs were behind the times. The realization that dinosaurs were extremely active, birdlike creatures opened a world of color possibilities to dinosaur artists. And some of those paleo-illustrators have had no trouble going overboard: think *Deinonychus* draped in neon colors, like a Cretaceous Cyndi Lauper. For the most part, though, artists turned to the natural world around them for some clues about dinosaur color. The paleoartist Gregory S. Paul, in his classic book *Predatory Dinosaurs of the World*, laid out a few rules for shading dinosaurs. "Since big living reptiles, birds, and mammals are never gaily colored like many small reptiles and birds," Paul wrote, "one can assume that subdued colors were true of the big predatory dinosaurs, also, which to human sensibilities gives them a dignified air appropriate to their dimensions and power." Stripes, spots, or patches of iridescent color around the snout are acceptable, Paul said, but duller color schemes are the most practical.

But dinosaur color is no longer strictly the realm of speculation and artistic taste. Living dinosaurs, as well as fossils bearing impressive plumage, have provided an unprecedented window into prehistory. The key to the whole puzzle is a simple, beautiful fact that has irrevocably changed the way we look at dinosaur lives. It is simply this: birds are dinosaurs. It's a strange notion to think that the little hummingbirds that come to sip from the feeder planted just outside my window are part of the sole surviving dinosaur lineage, but there's no doubt about it: the Age of Dinosaurs continues. Birds just so happened to be the one dinosaur lineage that survived the end-Cretaceous extinction. It took more than a century for scientists to agree on this point, and it's worth taking a moment to consider the long history of the debate and how it relates to what our extinct dinosaur friends looked like.

There has always been one critical fossil that comes up in the discussions paleontologists have about the origins of birds: *Archaeopteryx*. Described in 1861 from a feather and a partial, feathery skeleton discovered in a German limestone quarry, this mosaic of reptilian and avian traits has been the keystone for varying theories about how birds originated. Lately, a slew of dinosaurs with plumage has led paleontologists to question what *Archaeopteryx* really was.

I remember exactly where I was when *Archaeopteryx* was threatened with demotion from its place as an evolutionary icon. I was sitting at an Exxon station in the middle of nowhere Montana, waiting for my rented SUV to finish fueling so I could continue my journey from the isolated town of Ekalaka (where I had been looking for dinosaurs with the paleontologists Thomas Carr and Scott Williams and their field crews) down to Thermopolis, Wyoming. After running into the convenience store to buy the requisite snacks and caffeine for my seven-hour trip, I checked my messages to see if I had missed anything important while I was in the field. New dinosaur studies come out faster than you might imagine.

E-mails trickled into my inbox. Mostly junk. But then there was a spate of messages from the ever-prolific Dinosaur Mailing List, titled "Greg Paul is right (again); or 'Archie's not a birdy.'"

The title referred to an idea, suggested years ago by paleoartist Paul and others, that *Archaeopteryx* was not the earliest known bird, but in fact one of a *variety* of feather-covered dinosaurs more closely related to the famous predators *Deinonychus* and *Velociraptor*. The idea had been kicked around over the years without much enthusiasm, but a paper in *Nature* had been released that afternoon which shook up the bird family tree and punted *Archaeopteryx* off to the non-avian dinosaur branch.

I cursed my luck that I couldn't get the report at my roadside stop, but since I was the only one at the pumps, I didn't feel bad about taking a few extra minutes to see what news services were saying about the theory. If there's anything reporters love more than a story about *Tyrannosaurus rex*, it's a story claiming that some facet of dinosauriana we had taken for granted has turned out to be wrong.

The splash of articles on the study didn't disappoint. "'Oldest bird' Archaeopteryx knocked off its perch in controversial new study," said one. Another baited evolution denialists with the title "Newly discovered dinosaur could disprove 'earliest bird' theory," although the article itself only stumbled through a litany of tidbits about Archie and a new feathered dinosaur dubbed *Xiaotingia*.

Apparently, after analyzing the evolutionary relationships of *Xiaotingia*, the paleontologist Xu Xing and colleagues found that both *Xiaotingia* and *Archaeopteryx* were more closely related to feathered but non-avian dinosaurs like *Velociraptor*. Bizarre, poorly understood forms such as *Epidexipteryx*—a small theropod decorated with ribbon-like feathers, with a mouth full of procumbent teeth—fell out closer to the ancestry of birds in this new evolutionary tree.

Depending on how you look at it, this was either a case of the best or worst possible timing. The entire reason I was on the road to Thermopolis—a tiny dot in the middle of Wyoming, best known for its hot springs—was to see the only *Archaeopteryx* specimen in the United States. If the report held true, the *urvogel* (original bird) had been cast down just a few hours before I was due to roll into town. "You've got to be kidding me," I thought as I pulled out of Exxon and started my long interstate drive.

Now, every *Archaeopteryx* specimen ever found—from a single isolated feather used to establish the creature's name in 1861 to the eleventh specimen announced in 2011—has come from southern Germany. The one I was going to see was one of the more recent discoveries, but we'll get to that in a moment. All the *Archaeopteryx* skeletons are preserved in limestone slabs that record the Jurassic life that sank to the bottom of an ancient sea that covered much of Europe around 150 million years ago. Crustaceans, fish, pterosaurs, small dinosaurs, and other creatures have all turned up in quarries, but the most cherished of all the fossils are those of *Archaeopteryx lithographica*. The high-definition preservation of these fossils not only recorded the anatomy of the creature's bones, but, in many of the specimens, vestiges of the feathers, too. That's what made the first *Archaeopteryx* skeleton ever found such a sensation.

Known as the "London specimen," the animal resembled certain dinosaurs in terms of its anatomy, yet *Archaeopteryx* clearly had feathers. Freshly embroiled in the controversy stirred by Charles Darwin's *On the Origin of Species* in 1859, Victorian evolutionists privately rejoiced that the creature was a confirmation that transformations from one kind of creature to another were actually possible. As the paleontologist Hugh Falconer called it, in a private letter, *Archaeopteryx* was a "strange being *à la* Darwin," and Richard Owen (who obtained the first skeletal specimen for what is now London's Natural History Museum) deemed *Archaeopteryx* to be the "by-fossil-remains-oldest-known feathered Vertebrate" and the earliest known bird.

Owen's ambitious plans for his museum were what brought *Archaeopteryx* to England. He wanted unique, dazzling fossils for his collection, and convinced the museum to front the cash for the

German fossil. Once everyone understood how important the early bird was German paleontologists were sore that their country's prize fossil had been so easily acquired by foreign scientists. While the second *Archaeopteryx* skeleton—called the "Berlin specimen," the most beautiful fossil of all time—was almost sold overseas to O. C. Marsh at Yale, and the cryptic Haarlem specimen—confused for a pterosaur until 1970—is held at the Teyler Museum in the Netherlands, all but two *Archaeopteryx* stayed in Germany. If you see an *Archaeopteryx* in an American museum, chances are that you're looking at a *cast* . . . unless you're in the middle of Wyoming.

Going by appearances alone, you'd never guess that Thermopolis contained anything as important as an *Archaeopteryx*. Faded signs along the highway leading to the isolated town give equal billing to the Wyoming Dinosaur Center and the "Safari Room"—a dining room decorated by the stuffed spoils of a big game hunter at the town's overpriced Days Inn. You know you're getting close to the local dinosaur showroom when you spot a metal *Allosaurus* skeleton on a street corner along the main drag, frozen as if roaring at the cars passing by.

I follow the suburban streets to the gravel parking lot outside the museum, anxious to get out of the sun and into the cool building where the famous fossil rests. The exterior of the Wyoming Dinosaur Center is as mundane as the drab dinosaurs I met in elementary school. There are no windows, columns, statues, or, really, much of anything. The gray building displays "Wyoming Dinosaur Center" in mismatched shades of green, and the whole structure baked in the heat of the August afternoon. I pay my ten-dollar entry fee and am directed by a disaffected young woman to a corridor that will lead me through the exhibits.

Contrary to its title, the Wyoming Dinosaur Center displays a variety of other forms of prehistoric life. The dinosaurs are the real draws, of course, and keep people moving along the hallway, past the petrified invertebrates and fossil fish. Along the way, I notice one large slab to the left of the path, depicting an aggregation of pancake-size ancient horseshoe-crab-like arthropods called trilobites; a nearby shelf displays a reproduction of the wormlike, schnozzle-faced invertebrate called a Tully monster (once a contender for the identity of the Loch Ness Monster, in fact); and a small alcove presents an array of early tetrapods, the amphibious vertebrates that were the first to clamber onto land around 375 million years ago. And then there are the dinosaurs. Some of the fossils on display are authentic. Others are casts, which isn't too surprising, given how difficult it is to put together heavy, invaluable bones of prehistoric creatures.

I didn't come for fiberglass dinosaurs. What I had driven all morning to see was the real thing, and there it was. Set behind a protective pane of glass, the Thermopolis *Archaeopteryx* rests in its limestone tomb. The skeleton, about the size of a raven's, was preserved in an odd pose, presenting the dinosaur as though it had fallen backwards off a bicycle—legs splayed, head thrown back, arms to the side, and all surrounded by the faint impressions of feathers. The little dinosaur's skeleton resembles the fierce anatomy of *Velociraptor*, but the array of feathers gives the *Archaeopteryx* fossil a subtly different character. I stand and stare at the fossil for a while, tracing its form along the slender toes and thin legs up the contorted spinal column to the animal's wishbone, still situated between the birdlike shoulders. A heavyset man and his tow-headed son, both decked out in the logos of their favorite sports teams, slowly amble past and don't pay the little slab much attention. The dramatic scene of a skeletal *Monolophosaurus* sinking its recurved teeth into the side of a long-necked *Bellusaurus* is apparently far more interesting and consistent with the character of the "terrible lizards."

They have no idea what they are missing! As I daydream about the bones, I wonder how this fossil wound up in such an isolated little town. Outside of Germany, I would have expected such a fossil to be on display in one of the venerated institutions further east—Chicago's Field Museum, the American Museum of Natural History in New York City, or Pittsburgh's Carnegie Museum of Natural History. What the hell was *Archaeopteryx* doing here?

It turns out that no one knows when this specimen was originally collected or where it was found. Rumor has it that the fossil was discovered some time in the 1970s, and the specimen was effectively a private secret until 2001, when a Swiss collector's widow offered it for purchase to Germany's Senckenberg Museum in Frankfurt. The museum declined, but in 2005 Burkhard Pohl of the Wyoming Dinosaur Center arranged a deal whereby the *Archaeopteryx* would be on long-term loan to the private museum. And even though fossils receive some protection in most federal states of Germany under Monument Protection Acts, Bavaria (where the *Archaeopteryx* fossils are found) doesn't have such a law, and so the export of the *Archaeopteryx* to Switzerland, and later to the United States, was perfectly legal, no matter how painful it was to see the specimen wind up at a commercial institution far from home. Too many countries have been robbed of their prehistoric heritage thanks to lax fossil regulations.

Had I visited the museum a day earlier, I wouldn't have given a second thought to what I was looking at. I would have taken it as current fact that, as it had been regarded for a century and a half, *Archaeopteryx* was the key to bird origins. Whether or not *Archaeopteryx* was a direct ancestor of later birds didn't matter—as the earliest bird, the feathered dinosaur represented the form of the very first avians. But now I had to wonder about the nature of the creature. Was the *Archaeopteryx* behind the glass truly an early bird, or a different kind of dinosaur simply hiding behind beautiful plumage?

I also knew that *Archaeopteryx* has always had a controversial place in our developing understanding of how birds evolved. Even around the time the fossil was originally discovered, and Richard Owen asserted that the bird lineage started with such a creature, other naturalists were not so sure. Darwin's friend and vociferous defender Thomas Henry Huxley sidelined *Archaeopteryx* as a weird animal that was almost entirely irrelevant to the question of bird origins. Instead, an influence on the evolutionary circumlocutions of German biologist Ernst Haeckel, Huxley proposed that the origin of modern birds went through a three-step process, starting with creatures similar to the small dinosaur *Compsognathus*, a diminutive theropod found in the same deposits as *Archaeopteryx*. "There is no evidence that *Compsognathus* possessed feathers; but, if it did, it would be hard indeed to say whether it should be called a reptilian bird or an avian reptile," Huxley wrote.

Contrary to what has so often been claimed on his behalf, Huxley didn't suggest that birds evolved directly from any known dinosaur, but proposed that something in the general form of *Compsognathus* was adapted into a flightless bird akin to an ostrich or an emu, and that these birds were the ancestors of flying birds. *Archaeopteryx* was just an evolutionary sideshow that illustrated that birds could possess reptilian traits, but did not fit anywhere into Huxley's scheme.

True to the often contentious nature of science, not everyone agreed with Huxley's proposal. Paleontologists such as Samuel Williston, Franz Nopsca, and O. C. Marsh hypothesized that birds really did have a direct dinosaurian origin. Exactly which dinosaurs was the real matter of debate. Some authorities favored the small, generally birdlike theropod dinosaurs, while others suggested that ornithischian dinosaurs such as *Hypsilophodon*—on the basis of their birdlike hips—were the true ancestors of birds. Still other naturalists mixed and matched these ideas. Perhaps some birds evolved from one dinosaur group, while the rest were derived from the other. Then again, Richard Owen and Harry Govier Seeley insisted that birds had evolved from pterosaurs, a different kind of archosaur that flew thanks to membranes stretched over an elongated finger. Huxley and other naturalists disputed this—the characteristics that united birds and pterosaurs were instances of convergence related to a similar lifestyle—but no one knew for certain exactly how birds evolved. And, despite Huxley's difference of opinion, *Archaeopteryx* became the singular touchstone for understanding the transition from reptile to bird. Any theory of bird origins had to take *Archaeopteryx* into account.

Even as paleontologists agreed that *Archaeopteryx* was the earliest bird, though, they were left with the question of what sort of reptile it had evolved from. The Scottish paleontologist Robert Broom suggested a solution in 1913 that made sense of the traits shared by dinosaurs, pterosaurs, *Archaeopteryx*, and other birds. Before the era of the pterosaurs and dinosaurs, during the earliest parts of the Triassic, the crocodile-like archosaurs ruled. One of these creatures, *Euparkeria*, was a bipedal, carnivorous croc relative that was old enough and generalized enough that it could be a common ancestor for dinosaurs, pterosaurs, and birds. If all three lineages evolved from such a creature—a common and relatively unspecialized rootstock—then that would explain why they were so perplexingly similar to each other.

It wasn't until an early-twentieth-century artist took up the question of bird origins that the answer was considered settled. Gerhard Heilmann was an accomplished illustrator as well as an amateur paleontologist, and in 1926 he published an English translation of a series of articles he had written in Danish called *The Origin of Birds*. I was fortunate enough to track down a copy a few years ago, and the book is a real treasure. The glossy pages are filled with detailed comparative drawings of bird and dinosaur skeletons, and Heilmann illustrated a few dinosaurs in active poses, such as a pair of *Iguanodon* sprinting over the Cretaceous plains. Heilmann's scientific argument was just as elegant as his drawings. Even though he acknowledged that some dinosaurs were birdlike, there was one feature that in his view barred dinosaurs from bird ancestry. Or rather, it was the lack of a feature. Heilmann knew that birds have a wishbone, or the modified set of clavicles known as a furcula. As far as Heilmann knew, no dinosaur had ever been found with these bones. Dinosaurs had apparently lost their clavicles during the course of evolution, and since a feature couldn't re-evolve once it had been lost, Heilmann reasoned, there was no way that dinosaurs could be ancestors of birds. The next closest group that had clavicles contained *Euparkeria* and its croc-like kin, and so Heilmann concluded that birds and dinosaurs had so many features in common because they had evolved from a common ancestor.

Paleontologists found Heilmann's argument very persuasive—so much so that they overlooked the fact that dinosaurs did indeed have clavicles! A wishbone can clearly be seen in a diagram of bones published with the description of the beaked theropod *Oviraptor* in 1924, and a wishbone was found among the bones of the small theropod dinosaur *Segisaurus*, described in 1936 from a skeleton found crouched in a birdlike, roosting position. Heilmann's hypothesis had become so entrenched that paleontologists somehow missed even seeing these clavicles, and the idea that birds and dinosaurs independently evolved from a common, crocodile-like ancestor remained in favor—until a sharp-clawed dinosaur cut through the debate.

In 1969, the Yale paleontologist John Ostrom named *Deinonychus antirrhopus* from a quarry full of partial skeletons in Montana. With grasping hands, a long, still tail, and, most remarkable of all, a hyperextendable toe capable of plunging the dinosaur's "terrible claw" into prey, this dinosaur was clearly an agile and active predator. *Deinonychus* seemed as different as could be from the traditional vision of idiotic, swamp-bound dinosaurs—like the ones Ostrom himself had helped design for the Sinclair pavilion of the 1964 World's Fair—but the osteology of this dinosaur was not totally unprecedented. *Deinonychus* was very birdlike, and Ostrom quickly recognized the similarity between his newfound predator and *Archaeopteryx*. The dinosaurian origin of birds had clawed its way back into the scientific spotlight.

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The idea that birds are dinosaur descendants changed our entire perception of what dinosaurs were. If modern birds are dinosaurs, and dinosaurs resembled avians, then long-held assumptions about dinosaur biology had to be wrong. Maybe not all dinosaurs hopped around like magpies or ran with the grace of an ostrich, but the links between *Archaeopteryx* and *Deinonychus* hinted that some bird traits—such as highly active metabolisms, warm body temperatures, and even feathers—originated deep within the dinosaur family tree.

A 1975 article by Bob Bakker, one of Ostrom's students and the guy who catalyzed the Dinosaur Renaissance, included a restoration of the Triassic dinosaur "*Syntarsus*" with feather-like scales and a crest of plumage on its head as a speculative tribute to the revamped avian dinosaur hypothesis. And, Bakker noted, such a view generated "a particularly happy implication" for dinosaur fans: "the dinosaurs are not extinct; the colorful and successful diversity of the living birds is a continuing expression of basic dinosaur biology."

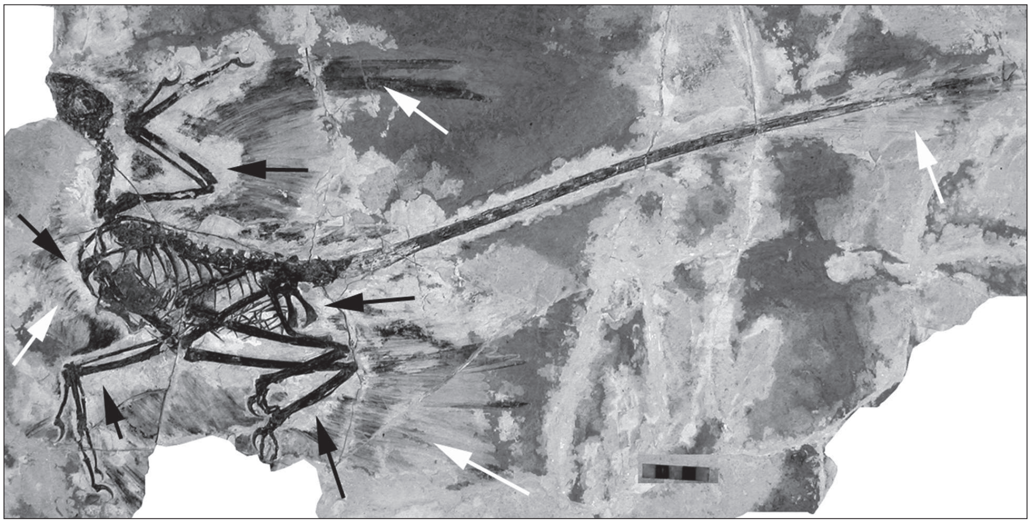
Ostrom's and Bakker's ideas filtered through to the documentaries I eagerly watched in my youth. One of my favorite shows was *The Dinosaurs!* on PBS. (Documentaries about the prehistoric celebrities in the late 1980s and early '90s regularly combined the word "dinosaur" with whatever number of exclamation points was desired to make their point, from *Dinosaur!* to *The Dinosaurs!* and the extra-emphatic *Dinosaurs! Dinosaurs! Dinosaurs!*) One Thanksgiving Day, PBS ran the entire four-part series in a dinosaur marathon, giving me hours of prehistory-fueled joy while the traditional holiday dinosaur, dressed and stuffed, was downstairs in the oven. In one episode, which highlighted the essential connection between dinosaurs and birds, a little green dinosaur—*Compsogntathus*, I presumed—ran through an ancient forest. As the chicken-legged beast climbed up a log, though, it quickly sprouted feathers and took on more of a confident strut, all before leaping into the air and metamorphosing into a modern pelican.

An episode of PBS's series *The Infinite Voyage* included a little more detail. A very fluffy *Deinonychus* went transparent, showing key bones in the skull, arms, hips, and legs, and as the dinosaur ran it transformed into an *Archaeopteryx* and, ultimately, took flight as a crane. On the outside, a modern bird and something like *Deinonychus* might seem drastically different, but when you look at their skeletal framework, the differences aren't so extreme, after all.

Despite all this conditioning, I still thought feathered dinosaurs looked silly. Dinosaurs were supposed to look mean and scabrous. With feathers on, *Velociraptor* just looked like a big chicken. Plush, downy dinosaurs in gift shops did nothing for me. They looked far too cuddly to be adept flesh-renders. *Jurassic Park* entrenched visions of olive-green, scaly carnivores in my young mind, and even now, there are some absolutely daffy feathered dinosaurs that I feel downright embarrassed for. One of the worst models is on display in Las Vegas—a *Deinonychus* plastered with feathers, creating what I can only imagine is some Cretaceous version of Robert Smith from The Cure. Mounts like *this* one may do more harm than good in communicating our new image of dinosaurs—a vision in which scaly hides have given way to feathery ones. Like it or not, many dinosaurs were fuzzy, fluffy, and feathery.

Feathers have a very deep evolutionary history. Their trail goes much deeper than the earliest birds, and may even go back as far as the first dinosaurs. Indeed, a flood of fossils discovered over the past fifteen years have irrefutably shown that most, if not all, dinosaur lineages had some kind of feather-like body covering.

The first fluffy dinosaur discovery enthralled paleontologists. At the annual Society of Vertebrate Paleontology conference in 1996, scientists circulated a photograph of a small fossil that revealed a mane of fuzz along a dinosaur's back and tail. John Ostrom, who was chiefly responsible for reinvigorating the idea that birds are dinosaurs, was "in a state of shock" after hearing the



Microraptor **is one of more than thirty feathered non-avian dinosaurs found so far. (The white arrows point to feathers on this dinosaur, and the black arrows indicate more subtle feather traces that can be seen only under UV light.) By studying the microscopic structure of *Microraptor* feathers, paleontologists have even discovered that this dinosaur had dark, glossy feathers. In life, it looked something like a toothy raven.** **(Image from www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0009223)**

news. At long last, a feathery non-avian dinosaur had really been found. This creature, labeled *Sinosauropteryx* in a technical publication the same year, didn't have feathers suited for flying. The simple dinofuzz covering the creature's body could only have been for display and insulation—the dinosaur lacked the specialized, asymmetrical feathers that allow modern birds to take to the air. In fact, it would have looked very much like Huxley's hypothetical feathery *Compsognathus*. The newfound dinosaur pointed to the hypothesis that feathers were not originally used for flight, but had evolved for different reasons and were later co-opted.

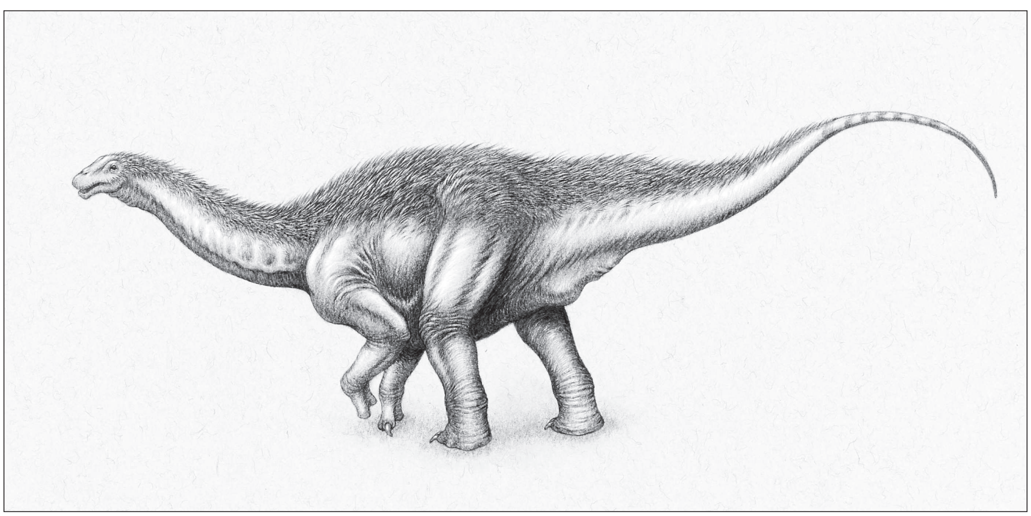
At least thirty different feathery non-avian dinosaurs have been recognized since that first one. Some are more "birdlike" than others. *Anchiornis*—a roughly 160-million-year-old, pigeon-size dinosaur—had elongated feathers on its arms and legs that might represent an intermediate state between wholly terrestrial dinosaurs and early fliers. And even *Velociraptor*, a turkey-size predator that most certainly did not fly, had elongated feathers on its arms—a feature inferred from quill knobs preserved on the dinosaur's arm bones. If there is ever a *Jurassic Park 4*, and that movie has *Velociraptor* reprise its role, the dinosaur should sport some exquisite plumage, Steven Spielberg's sense of taste be damned.

Even bizarre dinosaurs further removed from the avian rootstock sported decorative, feather-like structures. *Beipiaosaurus inexpectus*—a potbellied dinosaur with long claws, an extended neck, and a beaked skull better suited to clipping plants than slicing flesh—was enveloped in two layers of differentiated, simplified, elongated feathers. Tyrannosaurs had feathers, too. A small form named *Dilong* and a much more formidable, 30-foot genus called *Yutyrannus* had filamentous coats of fuzz. Thanks to these finds, we can say that *Tyrannosaurus rex* was probably a feathery giant—an idea that will undoubtedly cause dinosaur traditionalists to have a conniption.

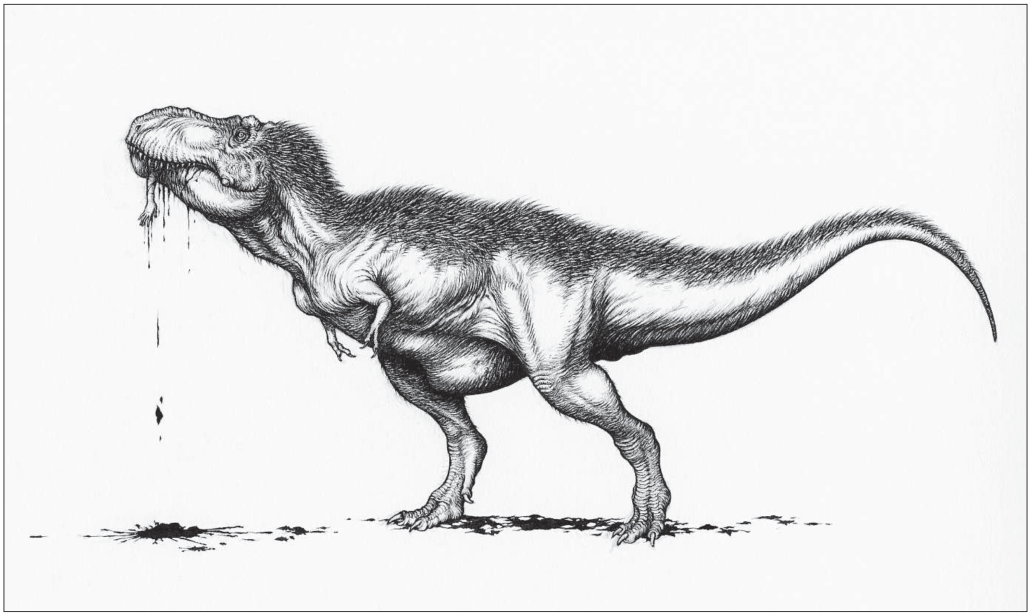
Feathers were not just a feature of birds and their closest non-avian predecessors. Birds are just one lineage of a wider theropod

Thanks to exquisitely preserved skeletons with intact gut contents, we know that fuzzy dinosaurs such as *Sinocalliopteryx* fed on their feathery neighbors, including other non-avian dinosaurs (left) and early birds (right). **(Art by Cheung Chung Tat. Image from www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0044012)**

family called the Coelurosauria. Every lineage within the Coelurosauria has at least one representative with dinofuzz or full-blown feathers. More than that, we now know that feathery adornments were a common dinosaur feature. Two dinosaurs—each about as far removed from birds as possible—also displayed body coverings structurally very similar to simple feathers. *Psittacosaurus*, which looks like an animal with a parrot head and a ceratopsian body, had an array of bristles along its tail. Even though most of its body was covered in scales, the bristles were very similar to the fluffy coatings found on theropod dinosaurs. And another dinosaur named *Tianyulong* sported a row of similar bristly ornaments along its back. These dinosaurs were ornithischians—forms that existed on the other side of the evolutionary tree from the coelurosaurs. Since creatures on both sides of the dinosaur family tree had feathers or feather-like body coverings, the fuzz and bristles might have been a common dinosaur feature, inherited from the last common ancestor of all dinosaurs. And the description of a fuzzy juvenile dinosaur named *Sciurumimus* in 2012—a dinosaur near the base of the theropod family tree, far from birds—added another feathery data point to the idea that protofeathers were



Even though there isn't any direct evidence yet, the discovery that many dinosaurs were partially covered in protofeathers means that some sauropods—such as this juvenile *Apatosaurus*—might have been fuzzy, too. **(Art by Niroot Puttapipat)**



Even *Tyrannosaurus rex* itself was probably coated in fuzz. Despite complaints from fans of scaly *T. rex*, the carnivore wouldn't have been any less fierce. **(Art by Niroot Puttapipat)**

widespread among dinosaurs. Most, if not all, dinosaur lineages might have had dinofuzz, and that includes the impressive sauropods. (Just think of how cute a fuzzy little *Apatosaurus* juvenile would be.)

We are left with only two possibilities. Either the same kind of simple filaments evolved over and over again, or dinofuzz was an ancient trait that was present in all dinosaur lineages. I can almost hear the scaly-tyrannosaur fans weeping.

The various types of prehistoric feathers cataloged so far outline how plumage has evolved. As far as paleontologists understand as of this writing, feathers started off as fuzz and in time were adapted into complex structures that allowed some dinosaurs to take to the air. Protofeathers were simple, single filaments. These are the kinds of structures seen on the bodies of *Psittacosaurus*, *Tianyulong*, and *Sciurumimus*. Archaic coelurosaurs—agile little dinosaurs like *Sinosauropteryx*, the first to be recognized with dinofuzz—had slightly more complex coats. Their protofeathers had multiple branches coming out of a central filament. These feathers were not all that different from those seen on oviraptorosaurs—beaked, omnivorous dinosaurs that were already quite birdlike to start with—as well as on parts of some true early birds. (Some feathered dinosaurs and early avians had multiple feather types on their bodies, just like modern birds.)

In the next stage of feather evolution, the individual filaments branched further along a central support. In dinosaurs such as *Microraptor* as well as in the earliest birds themselves, these individual filaments eventually formed true leaf-shaped feathers organized along a central vane. Some of these feathers, like those seen in the flightless raptors, couldn't support dinosaurs in the air, but *flying* dinosaurs—including *Archaeopteryx* and the four-winged *Microraptor*—had specialized, more aerodynamic feathers that were thinner along the leading edge. These were the feathers that finally allowed dinosaurs to invade the skies. Feathers originally formed insulating coats and flashy displays, and at least one lineage co-opted the same structures to become the only flying dinosaurs. Regardless of what *Archaeopteryx* was or was not, the gradual flow of scientific discoveries has revealed dinosaurs as increasingly birdlike and inextricably connected avian dinosaurs to their non-avian forerunners. Fossil feathers solved the mystery.

There's more to the dinosaur-bird connection than avian origins alone. Many of the fantastic new discoveries about dinosaur biology have been influenced by the fact that we have living dinosaurs to study. A chickadee isn't an *Ankylosaurus*, and an emu isn't a *Diplodocus*, but today's birds can help paleontologists refine questions and ideas about how dinosaurs lived. Best of all, our avian dinosaurs can finally help us fill out the palette of their extinct relatives.

As Charles Darwin wrote, "[I]gnorance more frequently begets confidence than does knowledge: it is those who know little, and not those who know much, who so positively assert that this or that problem will never be solved by science." Darwin was referring to humanity's origin—a mystery complicated by elusive evidence and dogmatic religious strictures—yet the same argument applies to the question of dinosaur colors. The problem was not an absolute lack of evidence, but the fact that the stepwise process of scientific understanding has only very recently grasped where to look for the essential clues.

I was reminded of Darwin's line while waiting for a session to start at the Society of Vertebrate Paleontology's 2011 meeting in Las Vegas—quite a setting for a conference on prehistoric life. The constant lights and buzz of Bally's grated on my every nerve, but I tolerated the cigar-smoking gamblers and the bagpiper who played on the street below until the early hours of the morning, because this was the temporary haven for the best and most cutting-edge info on paleontology. I had been waiting all year to hear about the new discoveries being made in the field and the lab. I especially wanted to hear what Brown University graduate student Ryan Carney had to say: he was set to reveal the true color of the first *Archaeopteryx* specimen ever found—the isolated feather used to name the dinosaur 150 years earlier.

The paleoartist Bob Walters sat down to my left a few minutes before the presentation was scheduled to start, notepad at the ready. I jokingly asked if he was angry at paleontologists who stepped on his turf and told him what colors were now considered acceptable. Bob looked shocked. "Not at all!" he said. Artists like Bob had long been hoping for some scientific indication of dinosaur color, he said, and now paleontologists were going to give them just that.

Once Carney took the stage, he didn't waste any time relaying the news of his team's discovery. The *Archaeopteryx* feather was black. Whether the whole animal was black was impossible to say. The single feather was selected because it was a famous specimen and it was the sesquicentennial anniversary of when the beloved feathered dinosaur was named, but nevertheless, the analysis had finally attached a color to one of the world's most important fossils.

The method by which Carney and his collaborators determined the dinosaur's hue was developed several years ago, and it all started with a squid. A very, very old squid, but a squid all the same. Jakob Vinther, a molecular paleobiology graduate student at Yale University, was inspecting the ink sacs of a fossil cephalopod under a high-powered electron microscope when he noticed little blobs inside the membranous pocket. Paleontologists had seen structures like these before and had assumed that they were fossilized bacteria, locked in stone as they started to break down prehistoric soft tissues. But the fact that the microscopic spheres were restricted to the inside of the ink sac suggested something different. These were melanosomes—tiny organelles whose shape, density, and distribution create pigment. In the squid, the melanosomes gave a dark-brown color to the ink the cephalopod used to escape from predators, and Vinther wondered if melanosomes might be detected in other fossils.

Feathers seemed a good place to look because many of their colors are created by melanosomes. If fossil feathers contained melanosomes, and zoologists could examine the feathers of modern birds to see how the organelles corresponded to certain colors, then they could reconstruct the colors of prehistoric creatures. Before Vinther and his collaborators could investigate non-avian dinosaur feathers, they had to establish that they were really seeing melanosomes and not bacteria. They did just that with a fossil feather from Cretaceous Brazil. The feather was banded white and black. If the little round bodies were bacteria, then they should have been found all over the feather's surface. As the researchers discovered, though, the tiny spheres were constrained to the dark sections only. These were the bands that would have carried pigment, and so the scientists could be confident that they had identified real melanosomes.

Vinther knew that the findings had applications for dinosaurs, too. A beaked, birdlike dinosaur named *Caudipteryx*, he and his team pointed out, had a fan of banded tail feathers that might actually represent the true color pattern of the dinosaur. But his study didn't catch the public's attention. This was 2008. The key to dinosaur color had just been found, and yet the implications didn't reach far beyond the small number of researchers who read the paper. Still, the scientists kept at it, and the following year, Vinther led another study on a 47-million-year-old feather found in Germany. This one, from a bird that lived about eighteen million years after the demise of the last non-avian dinosaurs, had an iridescent sheen in life.

Non-avian dinosaurs were next on Vinther's list. But as often happens in paleontology, another team got there first. On January 27, 2010, the Chinese Academy of Sciences paleontologist Zhang Fucheng and a team of collaborators published online a letter in *Nature* about the colors of Cretaceous birds and, for the first time, non-avian dinosaurs. Among other specimens, the team had selected a *Sinosauropteryx*—the fuzzy dinosaur that had marked the onset of a flood of feathered dinosaurs from China starting in 1996. From the time the dinosaur was described, it was apparent that the protofeathers along its tail had a banded pattern. The team took only a very limited sample, but concluded that the darker patches had been reddish-brown. *Sinosauropteryx* had a candy-cane tail that could have been used as a visual signal among these dinosaurs.

A week after the online announcement, Vinther's team countered with an even more detailed study in *Science*. It was the first time a non-avian dinosaur had been fully restored in color. The Beijing Museum of Natural History paleontologist Quanguo Li, Vinther, and collaborators worked with a specimen of *Anchiornis*. This small dinosaur was known from multiple, roughly 160-million-year-old specimens, and it looked something like a magpie. *Anchiornis* was black with swaths of white on its arm and leg feathers. But most impressive of all was a tuft of reddish plumage on the dinosaur's head. I hadn't seen anything like it before. *Anchiornis* looked rather plain, but in a strikingly beautiful way, made all the more wonderful by the fact that we could now tell what color dinosaurs were.

Both *Archaeopteryx* and *Anchiornis* were at least partly covered in black feathers. They looked like modern crows rather than birds of paradise. Vinther and colleagues found similar hues when they looked at the feathered dinosaur *Microraptor.* Using the same techniques on an absolutely gorgeous specimen of this sickle-clawed dinosaur, the team discovered that it boasted a glossy coat of complex feathers. Like *Anchiornis* and *Archaeopteryx*, *Microraptor* was a dark-colored dinosaur which wouldn't look out of place perching with the ravens along a western highway.

It never ceases to amaze me that we can now tease out dinosaur colors from the fossil record. The implications go far beyond the artist's palette choices. Whether stripes, spots, or iridescent plumage, feathered dinosaurs boasted visually arresting patterns. These dinosaurs were highly visual creatures who communicated with lovely, colorful displays. Even better, as we study more specimens from each species, we'll be able to investigate whether dinosaurs had different color patterns in each sex or distinct breeding plumage. Color might be the key to other aspects of dinosaur biology.

So far, the technique works only for dinosaurs with preserved feathers. For species of dinosaur that didn't have feathers, or even specimens of feathered species that were preserved without their plumage, we can't investigate their colors. We're also still looking for a way to detect and restore chemically created colors—some of the greens, blues, oranges, and yellows seen in many birds. As far as the science can reach, at least at the moment, there needs to be something to preserve the melanosomes and to be compared to modern analogs. You can't draw blood from stone, but if you know how to look, you can get dinosaur colors.

We're fleshing out the old bones that pack museums around the globe. We've uncovered intricately preserved specimens, reconstructed their body coverings, and now have a good sense of what they looked like. So with all of this in mind, how did dinosaurs see each other? Birds can see ultraviolet parts of the spectrum—could *Microraptor* have exchanged visual cues that we could never hope to see? What if there were a way to get inside a dinosaur's head, see the world through her eyes, and understand how she perceived her surroundings?