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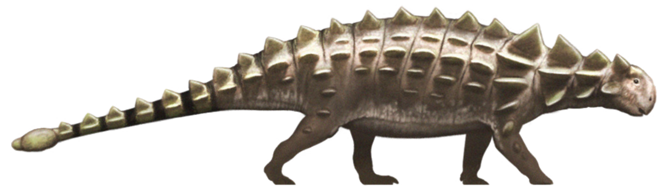
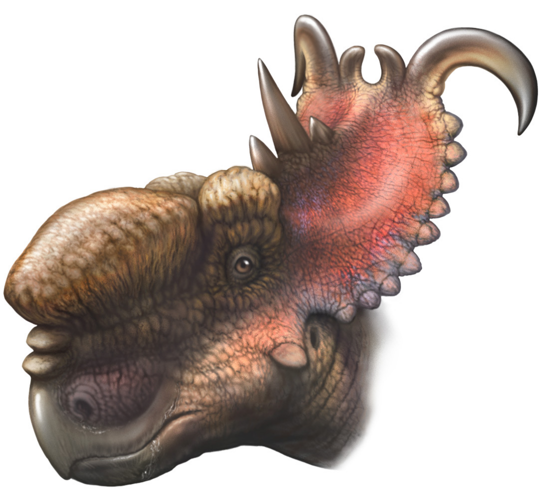




BIRDS AS A BRANCH OF THEROPODS

It's wonderful to know that birds are dinosaurs and you can see them every day; but birds arose in a remarkable way through the Jurassic period that involved a reduction in their body size.

When the first skeleton of the earliest bird *Archaeopteryx* was found in southern Germany in 1861, scientists realized this was a clue to the origin of birds. The fossil was clearly a bird, about the size and shape of a pigeon and with definite feathers preserved in the rock. But it had the skeleton of a small theropod.

For a long time, *Archaeopteryx* was the only fossil bird known from the Jurassic or Cretaceous—it had so many bird features, including feathers, wings, a fused clavicle (wishbone), hollow bones (to save weight), special wrist bones to enable it to fold its hand back, and big eyes and brain so it could see in three dimensions. Did this mean that birds had evolved really fast? The absence of older and younger bird fossils meant that *Archaeopteryx* became the subject of debate about rates of evolution, and even about whether evolution could explain the origin of such an amazing group as birds.

Today there are 10,000 species of birds, and these include many amazing flyers. How did this astonishing package of adaptations originate? Thanks to thousands of beautiful fossils from China, we now know much more than we did twenty years ago. These fossils include dinosaurs close to being birds and many other early birds from the Jurassic and Cretaceous. Three amazing facts are now known for sure: 1) Feathers did not arise with the origin of birds but much earlier, probably when dinosaurs arose in the Early Triassic; 2) Some dinosaurs could fly; 3) Birds and flight were possible because one lineage of theropods became smaller and smaller through the Jurassic, a process called miniaturization.

Let's look at *Microraptor*. This little dinosaur, a relative of *Deinonychus* from the United States, had birdlike flight feathers on its arms and legs, and recent calculations show

THE WORLD'S FIRST BIRD
This *Archaeopteryx*, from the Late Jurassic of Germany, is one of fifteen or so specimens, and it is kept in the Humboldt Museum in Berlin, Germany. Notice the dinosaur-like skeleton, but the modern, birdy feathers over its body, legs, and wings.

it could fly, flapping all four of its wings. How do we know it had feathers? The fossils show them clearly, and these allow aerodynamics experts to work out its effective wing area, and it turns out it could flap its wings and power through the air. We even know it had black, iridescent feathers.

So, not only are birds dinosaurs, and they evolved all their special flight adaptations over 50 million years before *Archaeopteryx*, but we now even know that some bird cousins such as *Microraptor* could fly, and this was a different kind of flight than seen in *Archaeopteryx* and in birds in general.

MINIATURIZATION

It's not common for animals to become smaller through time. In fact, the opposite is more usually the case, and this is so common that it has its own name, Cope's Rule. This idea was named after Edward Cope (1840–97), one of the greatest dinosaur paleontologists of the 1800s. He noticed that dinosaurs started small and grew bigger through time. It was the same for horses: the first horses were about the size of a terrier dog, and through 50 million years they became larger, up to the size of modern horses.

It's easy perhaps to see why Cope's Rule is so common in animal evolution. Being big has many advantages, such as being able to dominate your landscape. If you are a herbivore, you can get all the food and escape being attacked, such as modern elephants, and if you are a carnivore, being large allows you to attack anything. There are costs, of course, in being large, such as that you need more food, it takes longer to reach breeding age, and your babies take forever to grow up.

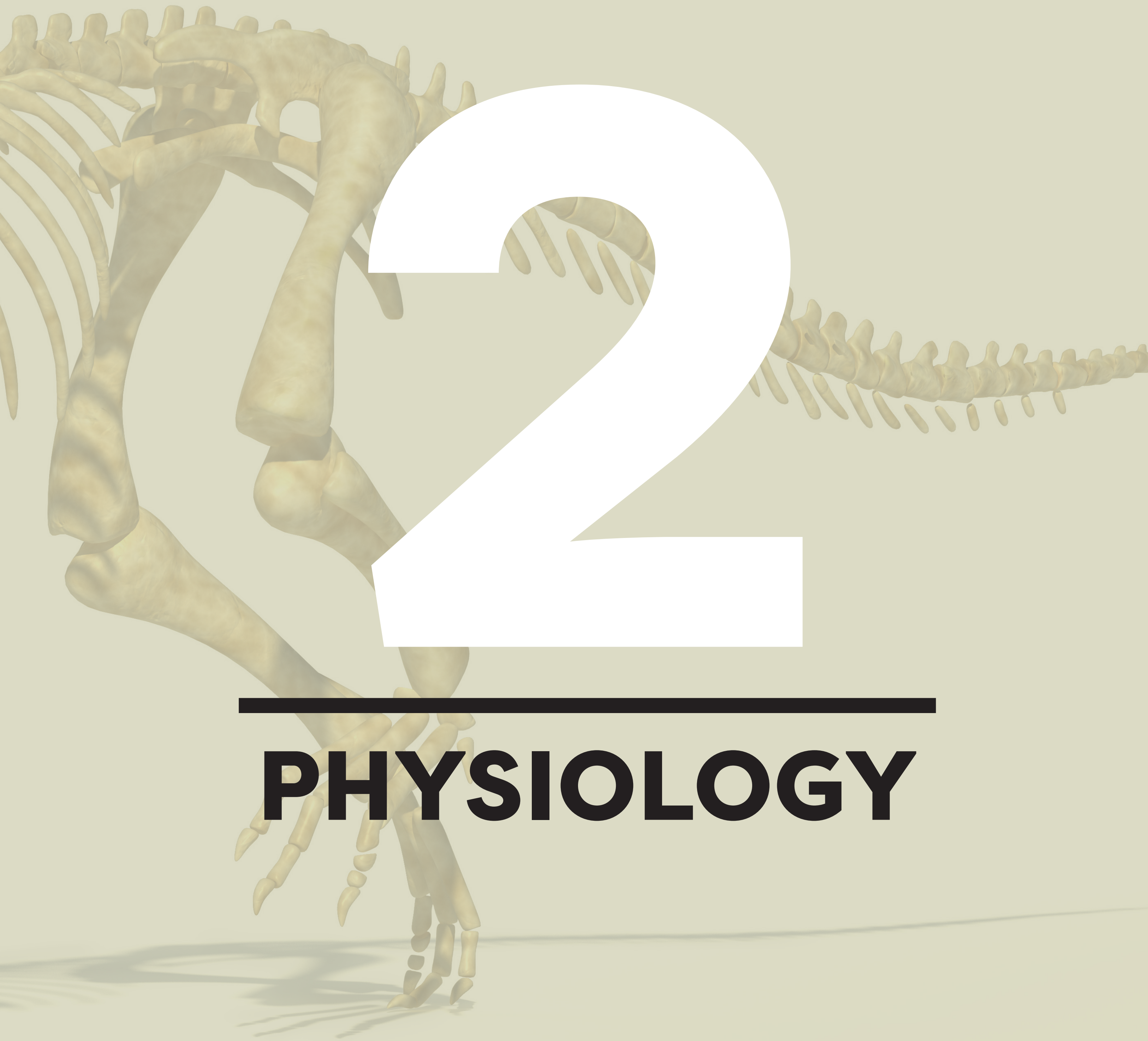
OPPOSITE
The skeleton of *Microraptor* shows all the features of a maniraptoran dinosaur, but there are lines of elaborate flight feathers along the arm and leg. In the fossil, the dark tips of the feathers show up against the rock.

IN FLIGHT
Microraptor, a dromaeosaurid like *Deinonychus*, had flight-type feathers along its arms and legs, and aerodynamic calculations show it could take off and fly by flapping its front and back wings. So, some dinosaurs could fly—it wasn't just the birds!

So, while theropods such as *T. rex*, *Giganotosaurus*, *Carcharodontosaurus*, and *Spinosaurus* were becoming giants, each weighing about 5 tons, one group, the maniraptorans, were getting smaller. They started in the Triassic at about 15 ft (5 m) long and weighing 260 lb (120 kg), and over 50 million years through the Jurassic became smaller and smaller, eventually reaching chicken size weighing about 1 lb (0.5 kg).

At the same time, the arms and hands of the maniraptorans were getting longer and stronger. The name "maniraptoran" means hand-hunter, and they had long powerful fingers for grasping prey. Also, we now know from the Chinese fossils, their arms were lined with evenly spaced flight feathers, so from a certain point in the Jurassic they were capable of gliding, perhaps leaping from tree to tree in search of juicy insect prey. At a certain point, the balance of reducing body weight and increasing arm length and wing size meant they crossed the crucial point of take off in powered flight.

As we shall see (page 98), there is a particular point at which a bird or an airplane can take off, which requires the correct ration between weight and wing area. Reducing weight (through miniaturization) is a great way to reach that point.



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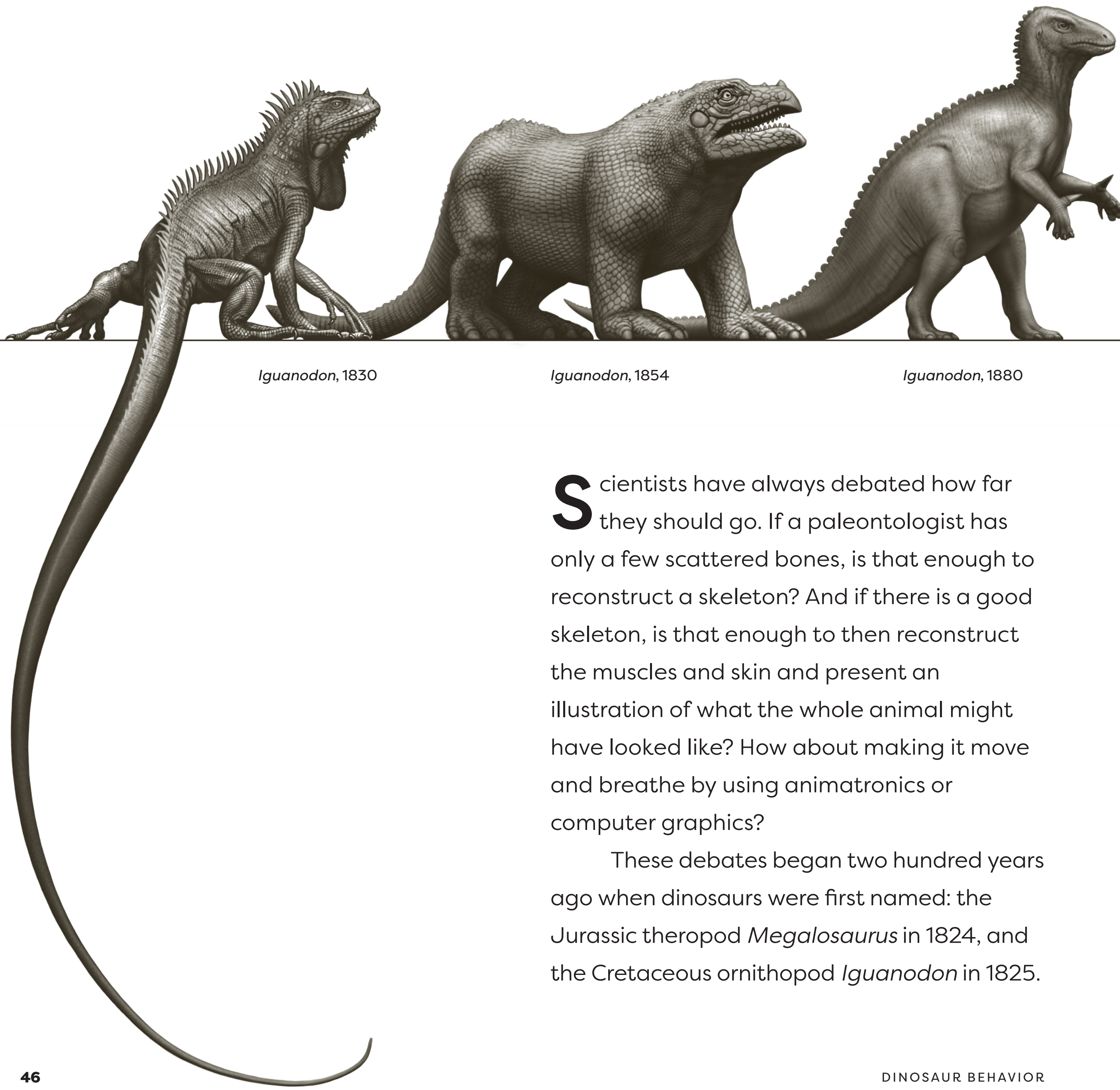
PHYSIOLOGY

VISUALIZING DINOSAURS

We have seen dinosaurs recreated in many different ways over the past two hundred years, and now, with new scientific understanding there are some amazingly realistic models, artwork, and even movies.



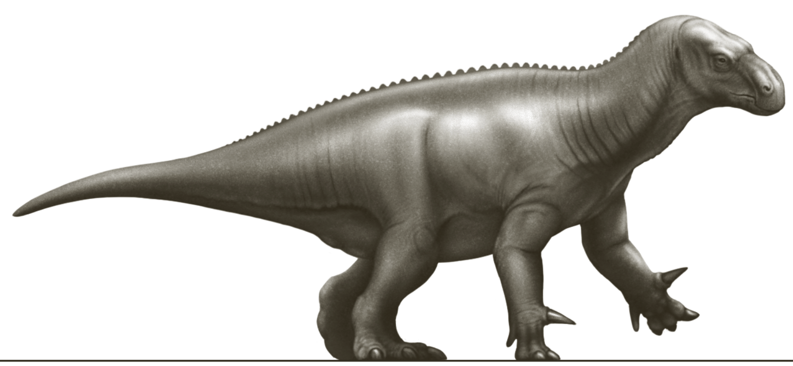
Iguanodon, 1830

Iguanodon, 1854

Iguanodon, 1880

Scientists have always debated how far they should go. If a paleontologist has only a few scattered bones, is that enough to reconstruct a skeleton? And if there is a good skeleton, is that enough to then reconstruct the muscles and skin and present an illustration of what the whole animal might have looked like? How about making it move and breathe by using animatronics or computer graphics?

These debates began two hundred years ago when dinosaurs were first named: the Jurassic theropod *Megalosaurus* in 1824, and the Cretaceous ornithopod *Iguanodon* in 1825.



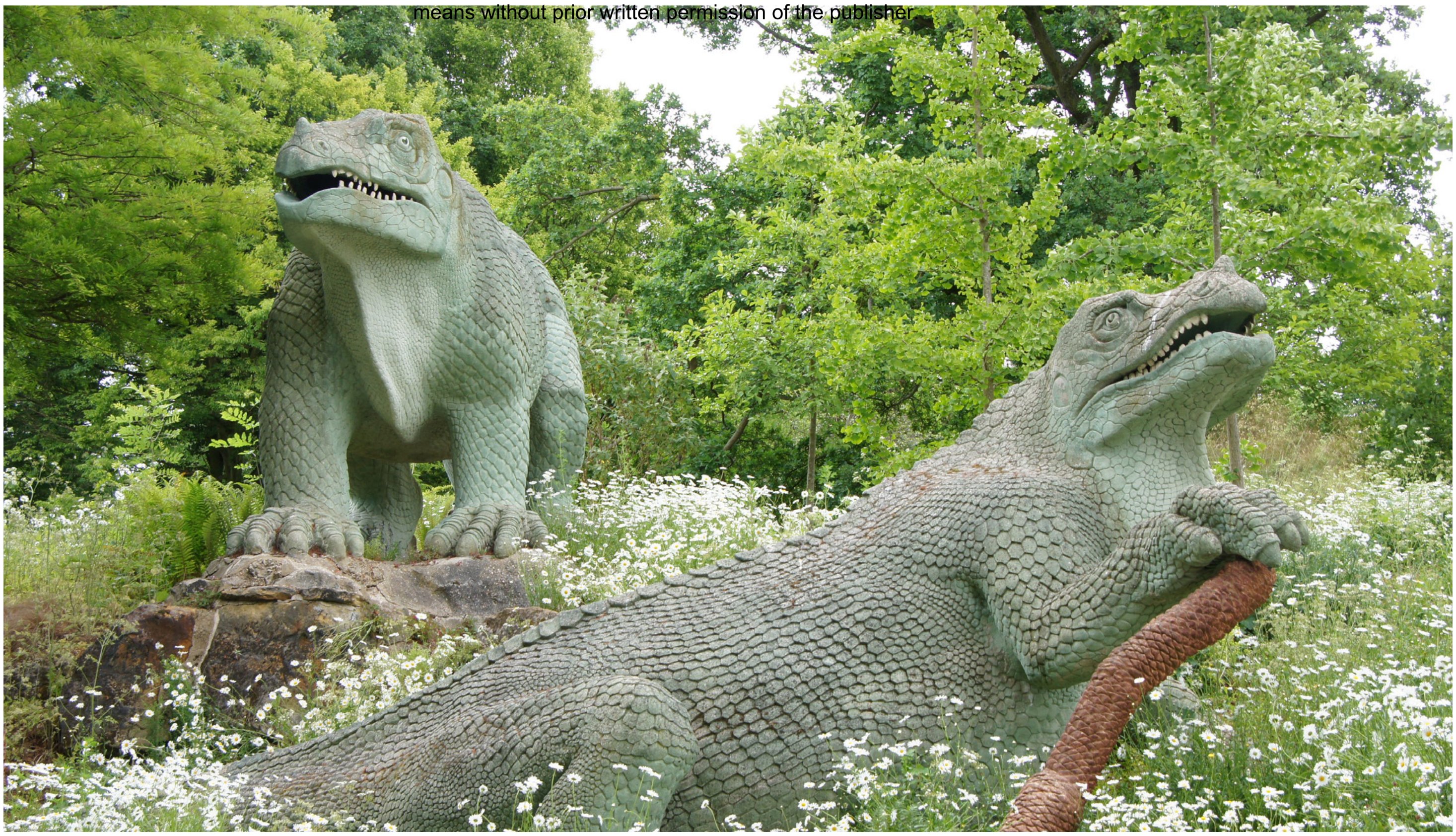
Iguanodon, modern-day

DINOSAUR IMAGE EVOLUTION
Here, the sequence from left to right shows *Iguanodon* first as something like a giant *Iguana* lizard, in about 1830, and then as it was reconstructed in 1854 for a life-sized model on show in London. Then, after complete skeletons were found, we see an upright, bipedal stance, something like a kangaroo. The modern reconstruction shows a more balanced biped, sometimes walking on all fours.

Was the job of a paleontologist simply to illustrate the fossil bones and not to make any guesses about what the animal looked like when it was alive, and even what it ate and how it behaved? Or, on the other hand, should the paleontologist use all the clues available to show people the best understanding they had of a lifelike dinosaur image or model?

The debate continues today, with some paleontologists seeing their job as simply presenting the science and not speculating or guessing about anything. They object to museum displays with lifelike paintings or animated dinosaur models. Other scientists believe they should share their work with the wider public, using models, paintings, and computer animation to do so.

Paleontologists attempted the first drawings of "living" dinosaurs in the 1820s, but the first reconstructions to hit the headlines were the famous Crystal Palace models unveiled in 1854. These were life-sized models made from steel and concrete by the artist Benjamin Waterhouse Hawkins (1807–94), and they were a huge hit with the public in London. Later, Charles R. Knight (1874–1953) produced the first modern-style paintings of all the newly discovered dinosaurs in the American West, and



OPPOSITE TOP
Two dinosaurs as reconstructed in 1854 for the Crystal Palace display by Waterhouse Hawkins. Here, two *Iguanodon* look fierce and scaly, with horns on their noses (later identified as their thumb claw).

OPPOSITE BELOW
A long-necked plesiosaur sits on the edge of the lake, which represents the sea. This reptile lived in the Jurassic oceans, where it hunted fish, swimming by beating its large front paddles.

BELOW
Two leathery-winged pterosaurs stand on a rocky cliff, planning their next move. Hawkins shows their long beaks, lined with sharp little teeth, ideal for trapping fish. Their wings are folded, but the pterosaur behind is extending its wings ready to take off.

his images were seen in the leading museums as well as in magazines and popular books.

Everything changed in the 1990s when artists could use computer-generated imagery (CGI) in movies such as *Jurassic Park* (1993) and the BBC documentary series *Walking with Dinosaurs* (1997). But times change. These early CGI films show dinosaurs with scaly skin, whereas we now know that many dinosaurs had feathers (see page 58). It's hard to know when we will be fully confident that our image of dinosaurs is finally correct and accurate, but paleontologists think we are getting there.

TOP
The famous scene in the first *Jurassic Park* movie in which an escaped *T. rex* menaces the hero. Here, the dinosaur is purely scaly, but the moviemakers took care in showing a slow running speed. Now, we would probably show *T. rex* with some feathers.

LEFT
The intrepid explorers of *The Lost World* see a *Stegosaurus* feeding on ferns and tree leaves. It's shown as active, with a high tail, not trailing along the ground as in older reconstructions.

FORENSICS:

PUTTING FLESH ON THE BONES

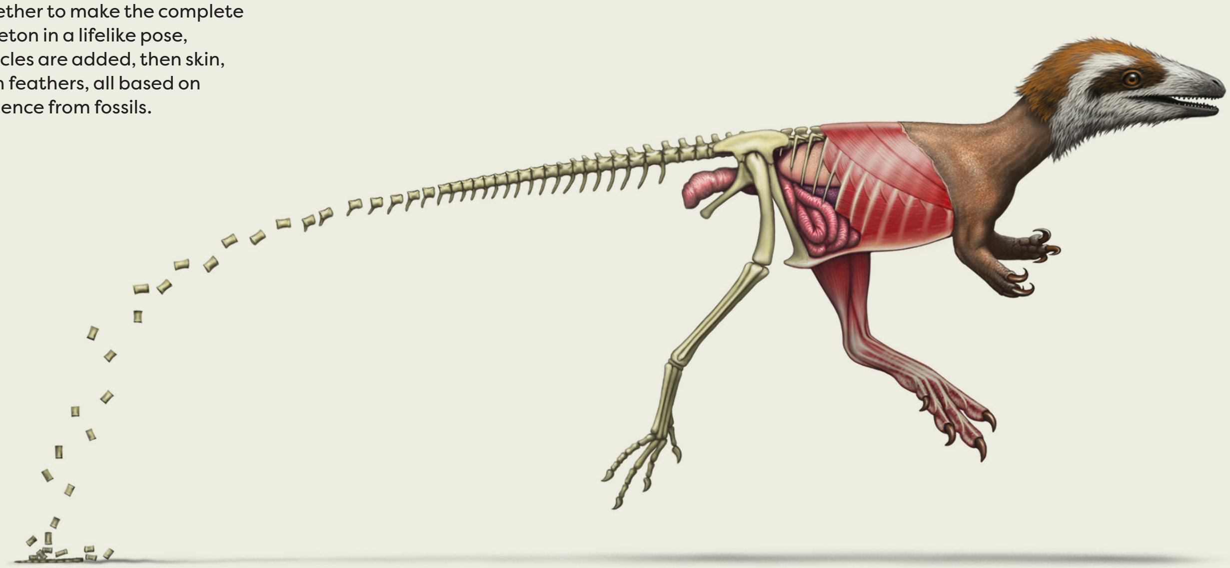
It's not just new digital technology that creates realistic-looking modern dinosaur illustrations; it is also our ever-growing knowledge from fossils. The recent dinosaur discoveries in China revolutionized everything. Before the 1990s, things were simple: birds have feathers, dinosaurs don't. Then, paleontologists in China began unearthing more and more dinosaurs with feathers (see page 58): first *Sinosauropteryx* in 1996, then *Caudipteryx* in 1998, and *Microraptor* in 2000. These three discoveries showed that many small theropods had feathers, and nobody knew where the new finds would end. Discoveries in 2002 showed that *Psittacosaurus* had feathers too, which was difficult to understand as this dinosaur was located far from birds in the evolutionary tree. Could it be that all dinosaurs had feathers?

Feathers give previously scaly dinosaurs a whole new look, and in 2010 paleontologists started to be able to identify the colors of dinosaur feathers (see page 172). This meant that paleoartists—those who make paintings and models of dinosaurs—sat up and paid attention. Everything they had done up to 2010 might now be wrong. No more scales, no more dull colors!

The image shown below of a *Sinosauropteryx* by paleoartist Bob Nicholls shows all the details of its feathers and their color patterns—and we are confident about these details because of remarkable fossil preservation. *Sinosauropteryx* was covered all over with short, bristly feathers, even on the tail and legs and over the face (see page 171). The fossils from China (see pages 60–1) show all the bones and feathers, and it is possible to identify the colors as ginger and white (see pages 172–3), and even the dark-colored "bandit mask" around the eyes.

Bob created this image digitally, using an art app, so he could generate each feather and scale as a separate element and fix the colors. New data can be used to edit the detail at any time, so the image is dynamic. It can be turned from a flat, two-dimensional image into a three-dimensional image for animation or display. Welcome to the new age of paleoart!

FLESHED OUT
From scattered bones (left) to living dinosaur (right). Here we see the sequence of fleshing out *Sinosauropteryx*, a feathered maniraptoran dinosaur. Its scattered tail bones are fitted together to make the complete skeleton in a lifelike pose, muscles are added, then skin, then feathers, all based on evidence from fossils.



MODERN REPTILES AND BIRDS

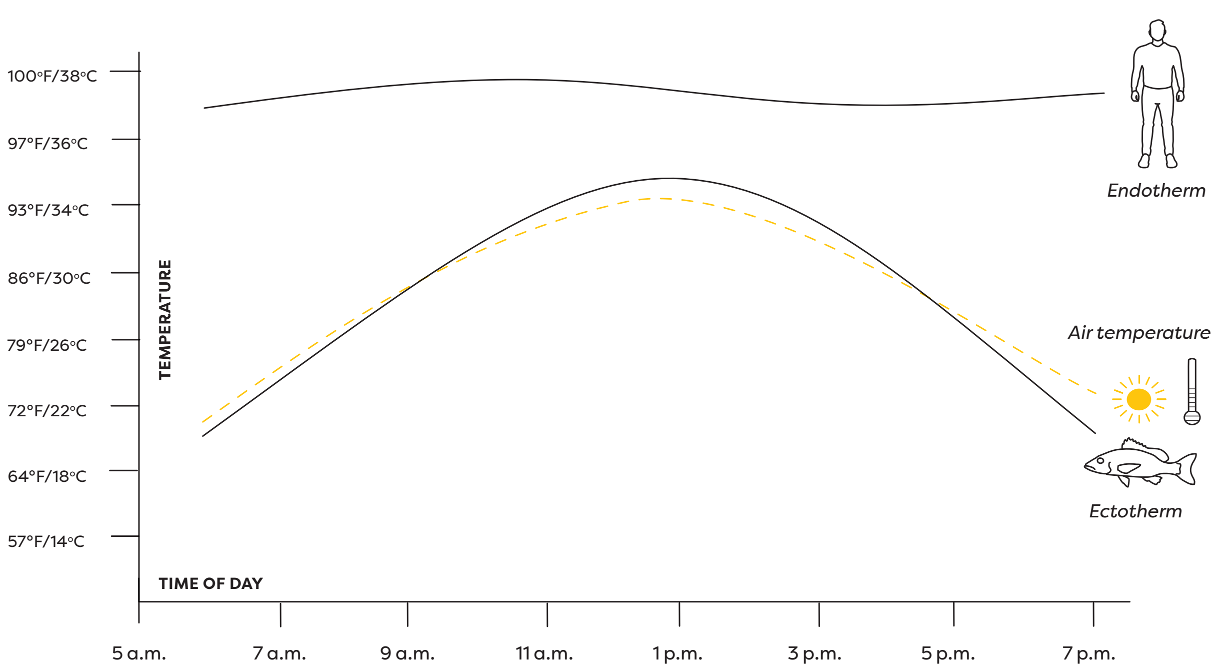
Understanding the physiology of modern reptiles and birds helps us to understand dinosaurs, and there are huge, significant differences between the functioning of the two.

At one time, paleontologists concentrated on modern reptiles such as lizards and crocodiles when they were reconstructing dinosaurs. The idea was that the dinosaurs were cold-blooded and slow-moving, just like an alligator in the zoo. The alligator enjoys lying out in the sun, absorbing the heat from its rays, and it moves only from time to time, and those movements are slow. It may wander over to the water and slide in for a lazy swim, or crawl on its belly toward a hunk of meat left by the zookeeper.

This is the classic depiction of a cold-blooded reptile. Lizards and crocodiles are ectothermic, meaning "external-heating." They get most of their warmth from the environment,

DAILY BODY TEMPERATURE

Warm-blooded animals (endotherms) show almost constant body temperature all day, whereas cold-blooded animals (ectotherms) can show body temperatures that vary up and down in line with changing air temperatures in the day and at night.



ARE ENDOTHERMS BETTER THAN ECTOTHERMS?
This (warm-blooded) egret might say so as it takes its perch on the back of a (cold-blooded) alligator. Different strategies for different modes of life.

by basking on rocks and absorbing heat from above and below. Small cold-blooded reptiles can run fast to escape, but they shoot under a rock as soon as they can because their energy levels are low and they cannot run far (see page 88). A big advantage for ectotherms, which prefer to live in warm climates, is that they don't need to eat much food.

Endotherms ("internal-heaters"), on the other hand, such as birds and mammals, have to eat plenty. An endotherm of the same body mass as an alligator, such as an ostrich or a human, has to eat ten times as much food each day because 90 percent of its diet is devoted to firing up the inner furnaces. Advantages for endotherms are that they can live all over the world, even in cold climates, because they generate their own heat and keep their body temperature constant. They can also hunt at night when the air is cold and other animals may be less alert. A constant body temperature means that all the chemical reactions inside the body are tuned to that temperature and can work highly efficiently.

These differences between ectotherms and endotherms are key parts of their physiology. "Physiology" refers to all the chemical processes in the body relating to feeding, breathing, energy transfer, water transfer, and use of the muscles. A key part of physiology is the metabolic rate of an animal: this is the rate at which oxygen is consumed. Ectotherms breathe at a low rate when they are not alarmed, whereas endotherms have higher rates of processing oxygen due to their faster, active, higher-intensity lifestyles.

So, do we see dinosaurs as lumbering around slowly and sleeping most of the time? Or do we see them as active, fast moving, and capable of complex behavior?

A SPECIAL KIND OF WARM-BLOODEDNESS

Cold-blooded or warm-blooded? The debate about dinosaur temperature regulation hugely affects how we interpret all aspects of their behavior.

Were dinosaurs ectotherms or endotherms? Up to about 1970, paleontologists were convinced they were ectotherms, but then evidence from detailed bone structure showed we should reinterpret them as endothermic. The bones show all kinds of evidence for this. First, the internal detail shows generally continuous growth and an open structure, as seen today in the bones of mammals and birds. Second, the bones show an overall microscopic structure typically seen today in birds and mammals (see "Bone histology," opposite). A third line of evidence in the bones of dinosaurs came to light in 2022, when Jasmina Wiemann of Yale University showed that nearly all dinosaurs were endothermic. She found high levels of particular organic waste chemicals in bones of birds, mammals, and dinosaurs, matching their high use of food, but these were absent in cold-blooded lizards and crocodiles.

A key point about many dinosaurs is that they were huge, and this gave them an automatic means by which to control variations in their body temperature. A small lizard, for example, warms up in daylight and cools down at night. An alligator warms and cools more slowly because of its size, and a dinosaur would have warmed and cooled yet more slowly. This gives an effect called mass homeothermy, meaning steady body temperature because of huge size.

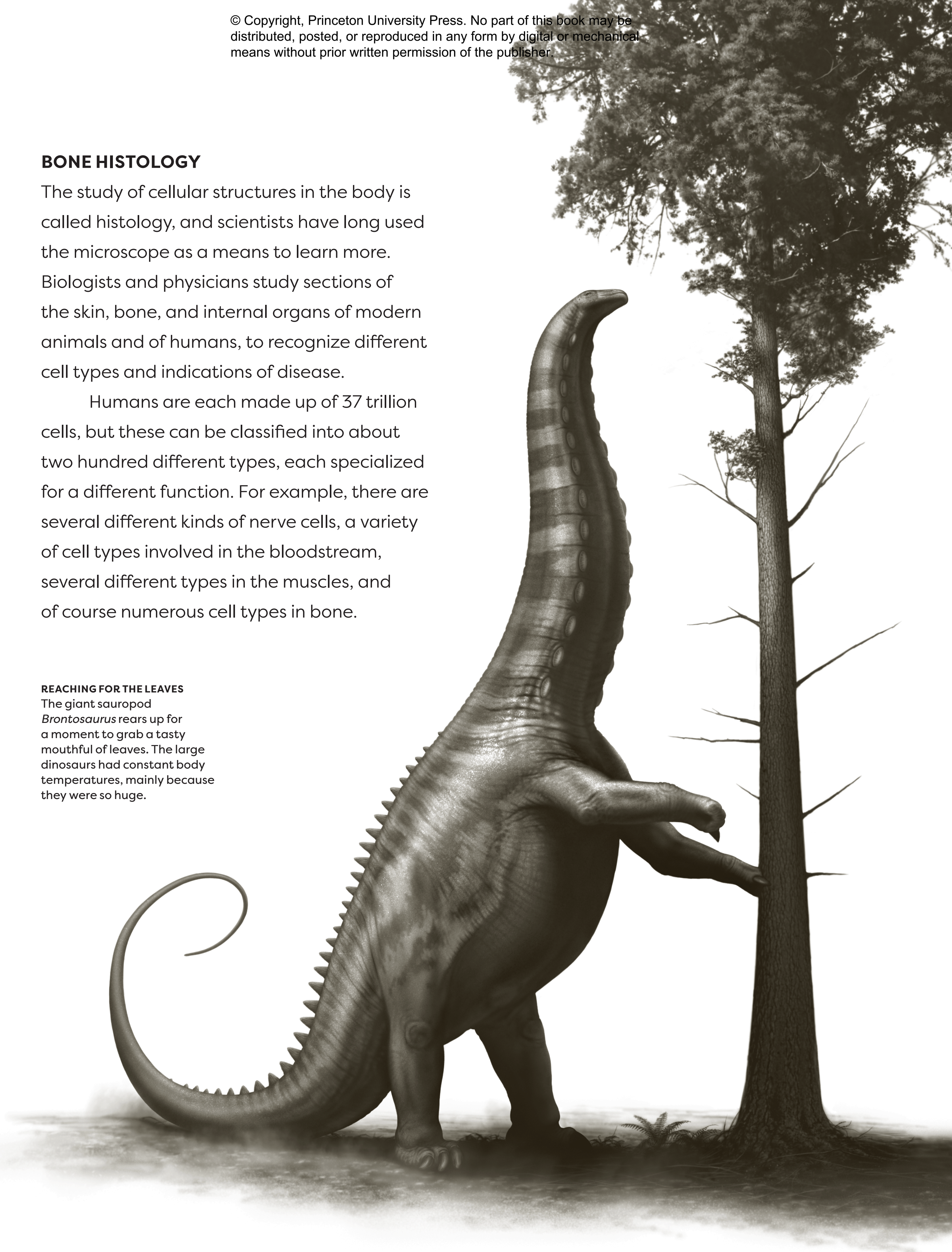
Mass homeothermy is a result of the surface-area-to-weight relationship. Small animals have lots of skin over their bodies relative to their mass, whereas the relative area in large animals is much smaller. This is why large endotherms such as elephants and whales need less food and oxygen per ton of body mass than smaller animals. Tiny endotherms such as mice and humming birds have to eat huge amounts and breathe superfast to take in enough oxygen to counter the loss of body heat from their tiny bodies.

So, a giant dinosaur such as *Brontosaurus,* which weighed ten times as much as an elephant and was also endothermic, probably did not have to eat ten times as much food as an elephant. It could rely on the natural properties of its huge body to retain core heat without any effort.

BONE HISTOLOGY

The study of cellular structures in the body is called histology, and scientists have long used the microscope as a means to learn more. Biologists and physicians study sections of the skin, bone, and internal organs of modern animals and of humans, to recognize different cell types and indications of disease.

Humans are each made up of 37 trillion cells, but these can be classified into about two hundred different types, each specialized for a different function. For example, there are several different kinds of nerve cells, a variety of cell types involved in the bloodstream, several different types in the muscles, and of course numerous cell types in bone.



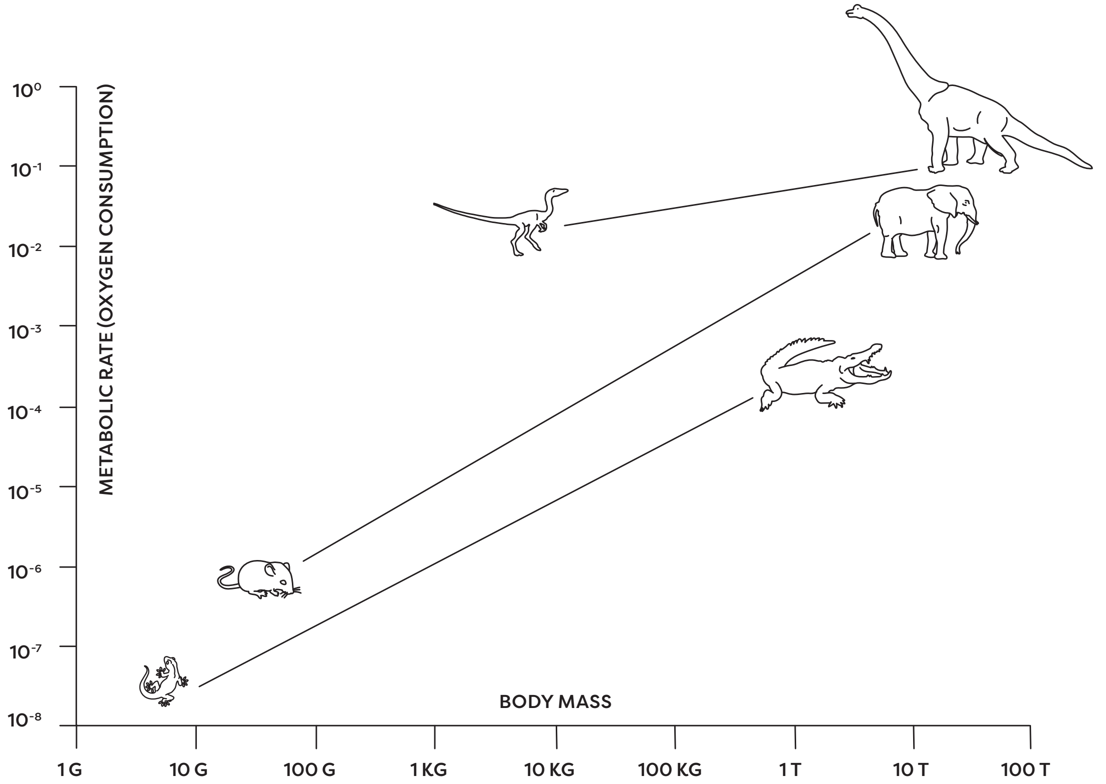
REACHING FOR THE LEAVES
The giant sauropod *Brontosaurus* rears up for a moment to grab a tasty mouthful of leaves. The large dinosaurs had constant body temperatures, mainly because they were so huge.

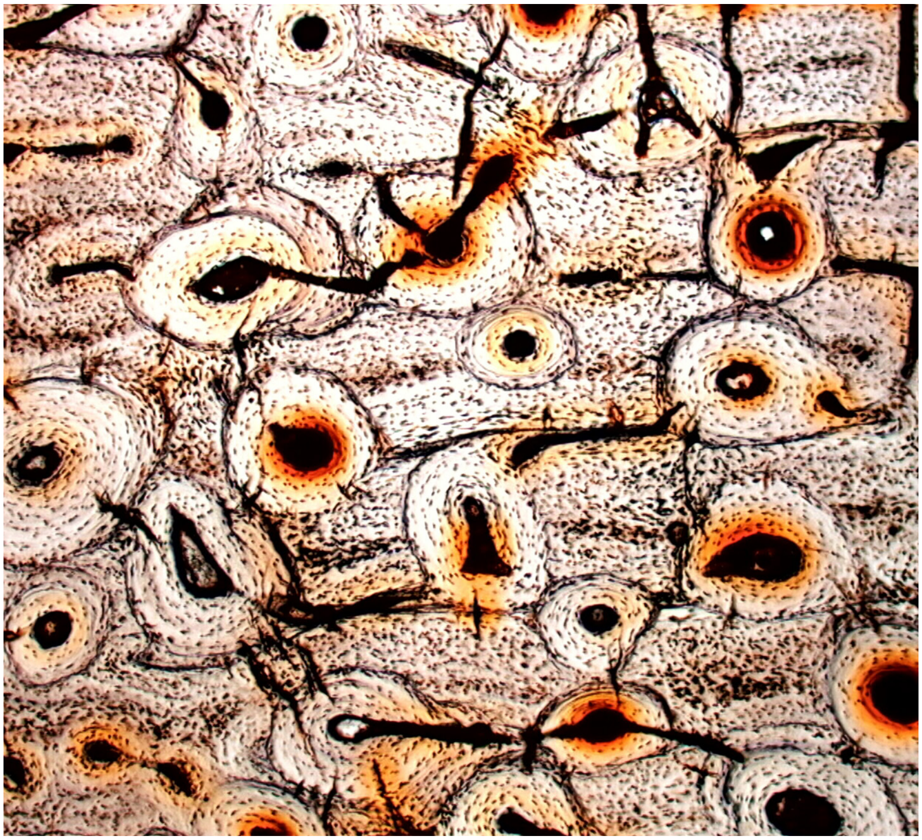
Bone is a living tissue, made from nerves, blood vessels, fat, flexible cartilage, and needle-shaped crystals of calcium phosphate (apatite) that form the hard structure. Living bone is partly flexible and partly brittle, and the degree of flexibility depends on age. For example, if a child falls over, they may be bruised and their bones may bend a bit then bounce back. If the child receives a harder knock, a bone may break, but provided the broken ends are realigned and the limb is bound up tightly with a splint, the bone will knit back together. In older people, the bones are less flexible and break more readily.

Bone structure differs between ectotherms and endotherms, and these differences can be seen in fossil bones. Paleontologists were amazed, over a hundred years ago, when they began to look at microscopic sections of fossil bone. Just as biologists take thin sections of tissues from modern animals, paleontologists can take a fossil bone and make a thin section—a very thin slice, thin enough to allow light to pass through but showing enough of the structure. Under the microscope, paleontologists saw that the detail of fossil bone could be as good as modern bone. Everything was there, and all that had changed was that the spaces filled with soft tissues such as blood vessels and fat were filled with minerals.

BODY SIZE AND METABOLIC RATE

Metabolic rate, measured in terms of oxygen consumption, increases with body size. Today, reptiles fall on a lower line than mammals because they consume less and require less oxygen because they are cold-blooded. Estimated values for dinosaurs fall high in the graph, much more in line with mammals than modern reptiles, because they too were probably warm-blooded.





SLICE OF BONE
A thin section (slice) through dinosaur bone, viewed under the microscope. It shows the so-called fibrolamellar structure throughout, composed of layers of pale-colored bone and showing darker spaces through which blood vessels and nerves ran. This kind of bone is associated with fast growth and warm-bloodedness. Superimposed on the background structure are larger circular structures called Haversian systems, which indicate sites where minerals have been eroded from the bone to fuel the dinosaur's growth. New bone has then been deposited in rings inside the tubes, filling inward and leaving a circular black space at the center where the blood vessel passes through.

In studies of dinosaur bone in the 1970s, paleontologists showed that it was usually of a type called fibrolamellar, meaning it was composed of regular, interconnected, open, layered structures. This is typical of the bone of living endotherms such as birds and mammals that experience fast growth.

Another feature of endotherms is called secondary Haversian remodeling. This is where the bone has been reworked, meaning that the original bone has been dissolved in places to acquire minerals into the bloodstream, then new bone has been laid down, creating overlapping circular structures called secondary Haversian systems. These systems are seen usually only in animals with high metabolic rates, where minerals such as calcium and phosphorus are needed in rich supply and fast, when the animal is particularly active.

Modern reptiles such as turtles, lizards, and crocodiles, on the other hand, typically do not develop these bone tissues, or not so frequently. Instead, they have a bone type called lamellar-zonal bone, showing cycles of growth. Also, they lack secondary Haversian remodeling. Both of these features suggest slower growth and lower metabolic rates, typical of a cold-blooded, or ectothermic, animal.

So, the high quality of fossils makes it possible to determine metabolic rates of dinosaurs from their bones, and it is clear that they were endothermic, or warm-blooded.

FEATHERS

Birds have feathers, but so did most dinosaurs. This is a new and still controversial idea, but the evidence appears to be clear, and it matches with their warm-bloodedness.

Older images always showed dinosaurs with scaly skins, like giant crocodiles or snakes. Indeed, many dinosaurs did have scales or bony plates in their skin, sometimes as a form of armor or simply to protect them from injury. In the 1970s, some researchers speculated that dinosaurs might have had feathers, but it was a discovery in 1996 that answered the question.

This was the year when the first feathered dinosaur, *Sinosauropteryx*, was announced from the Cretaceous of China. At first, some paleontologists did not believe it and said the simple, bristly feathers were bits of shredded scales or muscle. But over the following years, as more and more feathered dinosaurs were dug up in China, people had to accept the evidence: feathers were not unique to birds but were found in many dinosaurs, too.

What were these feathers for? In birds, feathers have three main functions: to insulate the body and keep it warm; specialized feathers for flight; and for display. In 2010 a way was found to tell the color of dinosaur

FEATHERS AND SCALES
The plant-eating dinosaur *Kulindadromeus* from the Jurassic of Russia shows an amazing mix of feathers and scales of different types over its body. Fossils have shown all this detail, including the broad armor-like scales down the tail, smaller scales over the legs, and tight feather covering elsewhere.

FEATHER TYPES
The seven types of feathers found in modern birds, from the pennaceous feathers of wing and tail on the left to fluffy down, contour, and semiplumes, and whiskery bristles and filoplumes on the right.

feathers (see page 172), and this showed they were colorful and probably used for display.

Then, in 2014 the further shocking discovery of an ornithischian dinosaur called *Kulindadromeus* with feathers meant that probably all dinosaurs had feathers, not just the theropods close to the origin of birds. Even more startling, in 2018 and again in 2022 evidence was published to show that the pterosaurs, the flying reptiles that are close cousins of dinosaurs, also had feathers. Pterosaurs and dinosaurs branched apart in the evolutionary tree back in the Early Triassic, (see page 35), so this suggests that the very first dinosaurs and their immediate ancestors also had feathers. Feathers perhaps first arose to provide insulation, then they became colorful and patterned for display, and finally the pennaceous feathers arose in theropods for gliding and flight.

ALL KINDS OF FEATHERS

There are many kinds of feathers, including simple whiskers, fluffy down, and pennaceous feathers. These are the feathers with a quill and branching barbs on each side, and they include the flight feathers in the wing as well as covert feathers over the shoulders, strengthening the wings, and on the tail.

In fact, modern birds have seven types of feathers, and these can be called generally either filaments or pennaceous feathers. The filaments include three forms. Bristles are stiff, and they are found around the eyes and face, providing some protection. Second are filoplumes, which are also stiff but have some small side branches called barbs, and have a sensory function—they are often located around the bird's beak and can be used to feel for prey such as insects that the bird wants to snap up. The third kind of filaments are down feathers, which are fluffy structures with many branches coming from the root, and they provide insulation, covering the bird's body.

The other four feather types are pennaceous, meaning they have a central quill, or rachis, and numerous side branches, or barbs. These are all larger feathers that form most of the wings and tail, and cover over the back. The first type is the semiplume, a feather with numerous barbs, but the barbs do not interlock, so these feathers are also fluffy, like down, and are mainly for insulation. Then, the contour feathers have barbs with tiny hooklets that can interlock and hold the shape of the feather. Contour feathers cover the top of a bird's wing and also extend over the back.

The sixth and seventh feather types are what people usually think about when they pick up a discarded feather from a pigeon or seagull. These are the tail feathers (retrices) and wing feathers (remiges), often long, with a rachis and lateral barbs, which form complete surfaces for flight. In these feathers, it is important that the whole structure is tough and air-tight. If, for example, either tail or flight feathers allowed air through, they would not function so effectively as solid surfaces.

We can see how important those feathers are when we watch birds. They often stretch out a wing and run their beak through the feathers, called preening. Preening is essential for removing seeds and parasites from the feathers, but also for lining up the barbs and removing gaps and knots between them.

DINOSAUR FEATHERS

When paleontologists began to identify feathers in dinosaurs such as *Sinosauropteryx*, *Caudipteryx*, and *Microraptor*, they seemed to fit the seven types of feather seen in modern birds. But then, something strange was noticed: some dinosaurs had feathers that were unlike anything seen in a modern dinosaur. For example, when Xu Xing and colleagues studied the oviraptorosaur theropod *Similicaudipteryx*, they found it had strange ribbon-like feathers, with a long, flat rachis, and a pennaceous tuft of branching barbs at the far end, like a flag. Looking closely at the feathers of other dinosaurs, they identified some other strange forms. For example, the Early Cretaceous ornithischian *Psittacosaurus* (see page 174) has a closely packed row of cylindrical bristles in a line along the middle of the tail; each feather is over 6 inches (16 cm) long, stiff, and standing upright.

The Middle Jurassic ornithopod *Kulindadromeus* from eastern Russia (see page 58) has a great range of types of scales and feathers, including bristles around the head and body, and pennant feathers all over the body—these have a circular basal plate from which five to seven slender filaments trail backward. These particular feathers are somehow halfway between scales and feathers, and indeed modern birds can have both. For example, a chicken has feathers all over its body, but its legs are scaly like a reptile. *Kulindadromeus* also had scaly legs, and a scaly tail. So it seems feathers and scales could be interchangeable in dinosaurs and birds.

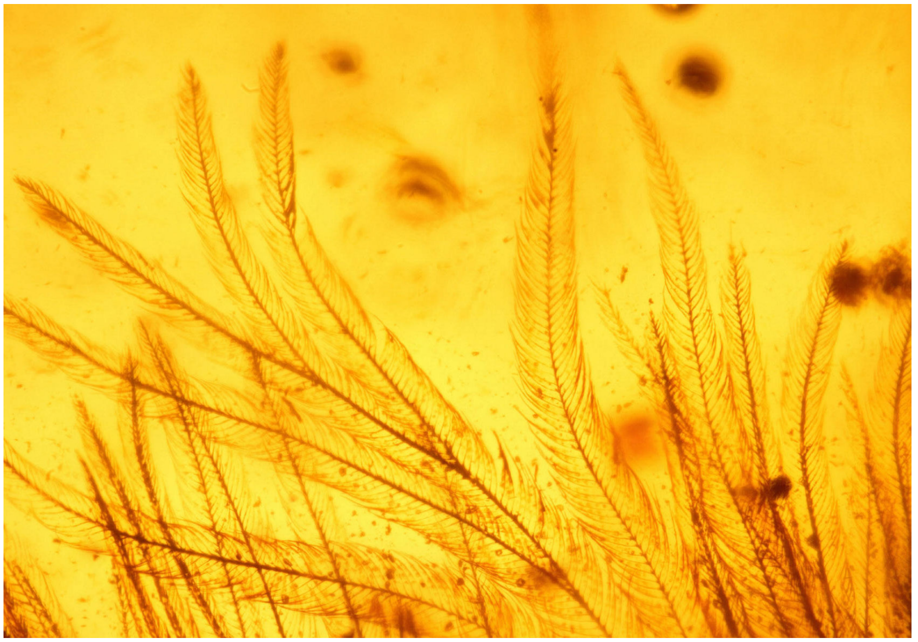
Recent studies of pterosaurs, the cousins of dinosaurs (see page 24), show that they had feathers too, and at least four types: simple bristles, bristles with a tuft at the end, bristles with a tuft halfway down, and down feathers.

It may be unexpected or shocking that dinosaurs and pterosaurs had feathers, and that they showed a greater variety of feather types than we see in modern birds. However, these Mesozoic reptiles existed for over 160 million years, and their feathers probably had many functions, so perhaps it is not surprising after all that so many amazing types of feathers evolved.

THE FOSSIL THAT CHANGED EVERYTHING
When this specimen of *Sinosauropteryx* was published in 1996, it was the first time that feathers were observed in something that was not a bird. Notice the bristle-like, short feathers over the back of the head, along the body, and in tufts down the tail.

PRESERVED IN AMBER

Amber is a remarkable substance: a transparent yellow-orange mineral formed by solidification of tree resin. Trees, especially conifers such as pine or spruce, produce glue-like resin to help heal breaks in their bark and other damage. Amber can be used as a semiprecious jewel, and pieces are sold to be worn as pendants, necklaces, or rings. Especially popular over the centuries have been amber pieces that contain a fossil insect. The insect may be well preserved, showing beautiful detail such as the fine whiskers on its



LEFT AND RIGHT
The most amazing dinosaur fossil ever? This tail of a small dinosaur is locked in amber and shows every detail of the long, branching feathers. These are definitely feathers, but there is nothing like them in any living bird. The whole specimen (right) would sit neatly in the palm of your hand (can you spot the ants?). In a close-up of the same specimen (left), you can see the tips of the long, whiskery pennaceous feathers—a type not seen in any bird.

legs, or beetles can show some of their original colors, for example.

Paleontologists have studied amber fossils for a long time, from specimens found in north Germany, the Dominican Republic in the Caribbean, and from Burma (Myanmar) in Southeast Asia. The amber from Burma has been especially exciting recently because some amazing specimens have been found in it, including tiny lizards, frogs, and even birds.

Burmese amber is Cretaceous in age, about 100 million years old, and it samples a huge variety of amazing tiny plants and animals. This was when new kinds of plants, the flowering plants or angiosperms, were appearing on Earth, and the new flowers attracted all kinds of new insects, which in turn were fed on by all kinds of new lizards, birds, and mammals.

Paleontologists used to joke about the "dream fossil": imagine finding a *dinosaur* in amber! But this seemed a ridiculous hope because dinosaurs are big and amber usually preserves only small animals. Then, in 2016 the miracle fossil was found. Well, in fact it was just a part of the tail of a very small dinosaur. However, this specimen of clear, pale yellow amber, a piece that would sit easily on the palm of your hand, shows a fluffy tail, with long, slender feathers. At first, paleontologists thought the fluff was made from hair and that this maybe came from an early mammal, but in close-up the long fluffy structures show numerous side barbs. They are feathers. How did paleontologists know it wasn't a long bird tail? Well, on X-ray-scanning the fossil, they found the skin, muscles, and bone preserved inside, and the bones were the tail bones of a dinosaur, not a bird.

BREATHING

Dinosaur breathing may have been super-efficient as in birds, and this was a smart way for them to be large and active at the same time.

Breathing is such a regular activity we don't usually think about it. We breathe in to take oxygen into the body, and we breathe out to expel the waste carbon dioxide. We know that our lungs process the gases, passing oxygen into the bloodstream, where it is carried around attached to red blood cells. After the oxygen has passed into the muscles and gut tissues, carbon dioxide returns into the bloodstream and back to the lungs. The oxygen passing through the body travels in the blood vessels called arteries, and the oxygenated blood is bright red. The returning blood is darker in color and passes through the veins and back to the lungs. The whole system is, of course, powered by the heart which pumps the blood through four chambers, allowing for so-called "double circulation," an efficient way to avoid mixing red oxygen-rich blood with the darker venous blood.

The system of breathing that mammals such as humans have is not entirely efficient. The problem is that we breathe in and out—a so-called tidal system—and when we breathe out, we don't entirely expel all the waste air. A volume remains in the lungs and breathing passages, and we pump in the next mouthful before clearing the old air. Birds, on the other hand, have a straight-through system, involving multiple air sacs as well as the lungs, and air goes in one way and out the other, so there is no dead space.

Dinosaurs almost certainly had the same system. There are no fossil lungs of dinosaurs, but there is evidence for the additional air sacs, shown by openings and hollow spaces in the vertebrae, the bones of the backbone, as well as in ribs and limb bones. This is called pneumatization, the invasion of bones by air sacs, both to save weight and to accommodate the air sacs. Weight-saving is important for birds to enable them to fly, but it's also important for large dinosaurs, to save weight. This is especially true of the long-necked sauropods, for example; with their air sacs, the neck weighs about half as much as it would if the bone were solid throughout.

The birdlike one-way breathing system in dinosaurs helped them to raise their metabolic rates and be endothermic, but at less cost than if they had had a tidal breathing system.

This is probably part of the smart set of adaptations they had to balance the costs of being large against the need to be able to move about reasonably actively, and without having to eat crazy amounts of food.

PNEUMATIC BONES

Modern birds and crocodiles have spaces inside their bones that in life are filled with air or fluid. The pneumatization of skull bones in crocodiles is probably a holdover from more ancient times when they perhaps had different modes of life or different respiration systems. Mammals even have some pneumatization; for example, humans have air sinuses inside the skull, above and below the eyes, and these spaces can become painful when you have a bad cold.

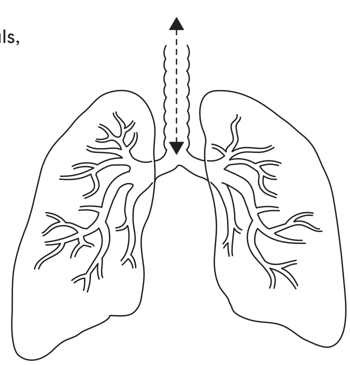
In birds the pneumatization is a key part of their metabolic system. Nearly all bird bones are hollow, but the hollow leg bones, for example, contain bone marrow, the spongy tissue in the body that produces red blood cells. The other hollow bones, in the vertebrae of the neck, trunk, and hip region, as well as their ribs, breastbone, and upper arm bones, are occupied by air sacs, balloon-like structures with an outer membrane and filled with air in life.

Why have such a complicated system? First, hollow bones save weight, and that's important for a flying bird as its success depends on flight ability. Air spaces can also help to rebalance an animal, by shifting weight back to the hips and tail, for example. Some birds even use their ability to pump air in and out of the air sacs as a way to survive when they fly up to great heights where air pressure is lower than near the ground.

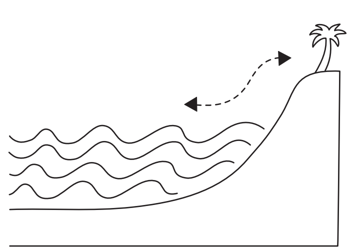
Dinosaurs did not have pneumatization for that reason, but weight-saving and rebalancing did matter. It was no surprise when paleontologists discovered that

BREATHING TYPES

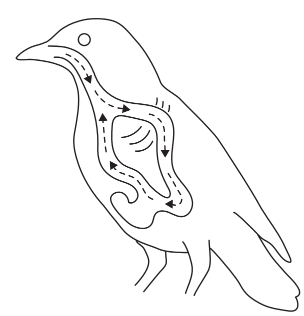
TIDAL BREATHING
In tidal breathing, as in humans and all mammals, the air goes in and out.



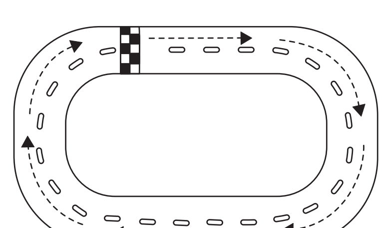
LIKE THE MOTION OF OCEAN TIDES



UNIDIRECTIONAL BREATHING
The air breathed in passes through a circuit, giving oxygen to the body and picking up carbon dioxide to breathe out.



LIKE THE MOTION ON A RACETRACK



sauropod dinosaurs had extensive pneumatization throughout nearly all of the vertebral column, from head to tail, as well as in their ribs and upper arm bones. It has been estimated that pneumatization makes the sauropod neck about half as heavy than if it were made from solid bone. And that matters if you have a 30-ft (10-m) long neck that has to be held up by huge muscles coming from the shoulder area.

What about the smaller theropods? Nearly all theropods, just like their descendants the birds, had hollow bones. In this case, it's a little about weight-saving for the larger examples such as *T. rex* and *Spinosaurus*. But it's as much for adjusting their balance. A typical large theropod saves weight in its forequarters, so its center of mass shifts backward to sit just above or in front of the hips. Theropods were all bipeds, walking just on their hind limbs, so keeping balance mattered, and it's been worked out that shifting the center of mass back a little would have increased their agility—especially their ability to twist and turn when chasing prey. And of course, it's also about improving their breathing systems. Dinosaurs shared the same one-way breathing system seen in birds, and that maybe gave them a 10 percent improvement in efficiency in transporting oxygen into the body and carbon dioxide out.

RESPIRATORY INFECTION

A huge *Brontosaurus* lumbers into view in the Late Jurassic landscape of tall conifer trees. It's a misty daybreak, with cold clouds of water vapor gathering over the lakes of the Morrison Formation scene. The *Brontosaurus* sneezes and snuffles. It lets rip with the largest sneeze ever. A small herd of browsing *Stegosaurus* look up nervously and shift further into the forest. The *Brontosaurus* plods on, breathing in and out with difficulty, making great roaring and rasping noises as it sucks air down into its lungs, and puffs it out again from the air sacs around its neck and torso. Great gobbets of snot fly from its nostrils as it puffs out a labored breath. Its head droops miserably. Here is a sick dinosaur.

How do we know dinosaurs suffered from respiratory diseases? This comes from a 2022 investigation by Cary Woodruff of the Great Plains Museum and Ewan Wolff at the University of New Mexico. They were studying a skeleton of *Brontosaurus* in the Museum of the Rockies, Montana, nicknamed Dolly. We have no idea whether Dolly was female or male, but the researchers argued they have clear evidence that this particular dinosaur was suffering from serious respiratory disease when it died.

The evidence comes from lesions, or unusual bone growths, on the vertebrae of Dolly's neck, just at the point where the air sacs entered the sides of the vertebrae. The bone lesions are irregular growths about 1 inch (2.5 cm) across on an otherwise flat structure, showing infection of the bone. The infection caused the bone to react while the animal was alive, growing unusually fast on the surface to try to respond to the attacking infections. In X-ray sections through the bone, the investigators found evidence of unusual and excessive bone growth in and below the lesions.

What could have caused the infections? It might have been a fungus, and such infections are seen in modern birds, termed aspergillosis. The fungal spores are microscopic and can enter the respiratory system through the nose or mouth, where the warm, damp environment encourages their growth. They then cause irritation within the breathing system, and a common response is that the membranes become red and infected, and they even attack the bone, which grows fast, attempting to overgrow or swamp the irritant. In modern birds, aspergillosis causes labored breathing, wheezing, sneezing, and over-production of mucus.

Dinosaurs didn't have vets, so they could not receive any medicine. However, aspergillosis is also a common disease of chickens and there is no cure, so Mesozoic medical aid would probably not have helped poor Dolly.

AAAHH . . . CHOO!
The biggest sneeze ever is made by this Jurassic *Apatosaurus*. It has a serious throat infection, similar to those found in modern birds.

FOOD BUDGETS

In many cases we know what dinosaurs ate, but working out how much they ate each day is difficult.

As we will see later (see page 70), paleontologists use all sorts of evidence to identify what particular food dinosaurs ate. The easiest thing to determine is whether they ate plants or meat, and then to compare all the dinosaurs and other beasts that lived together to work out a food web. A food web is a diagram that identifies who eats what.

Dinosaurs were parts of wider ecosystems; in other words, the whole network of species of plants and animals that lived together in a particular setting, and how they interact with one another. In many cases, paleontologists know a great deal about all the plants and animals that lived together, and the food web diagram may include different kinds of plants, pond life such as snails, shrimps, and fish, as well as land-dwellers such as lizards, crocodiles, pterosaurs, birds, mammals, and the dinosaurs.

Understanding something about a modern or ancient ecosystem allows biologists to understand how energy flows. Energy enters the ecosystem from the sun, and it is captured by plants that take in the sun's energy and convert carbon dioxide from the air and water that they draw up through their roots into oxygen and sugars. Plants consume the sugars to build their bodies, and they release oxygen through tiny holes in their leaves. This is why we value plants, and trees in particular: they produce the oxygen that animals and humans need to breathe. This conversion process, photosynthesis, happens on land and in the oceans, where tiny floating plants called phytoplankton perform the same process and produce oxygen that passes into the atmosphere and into the water.

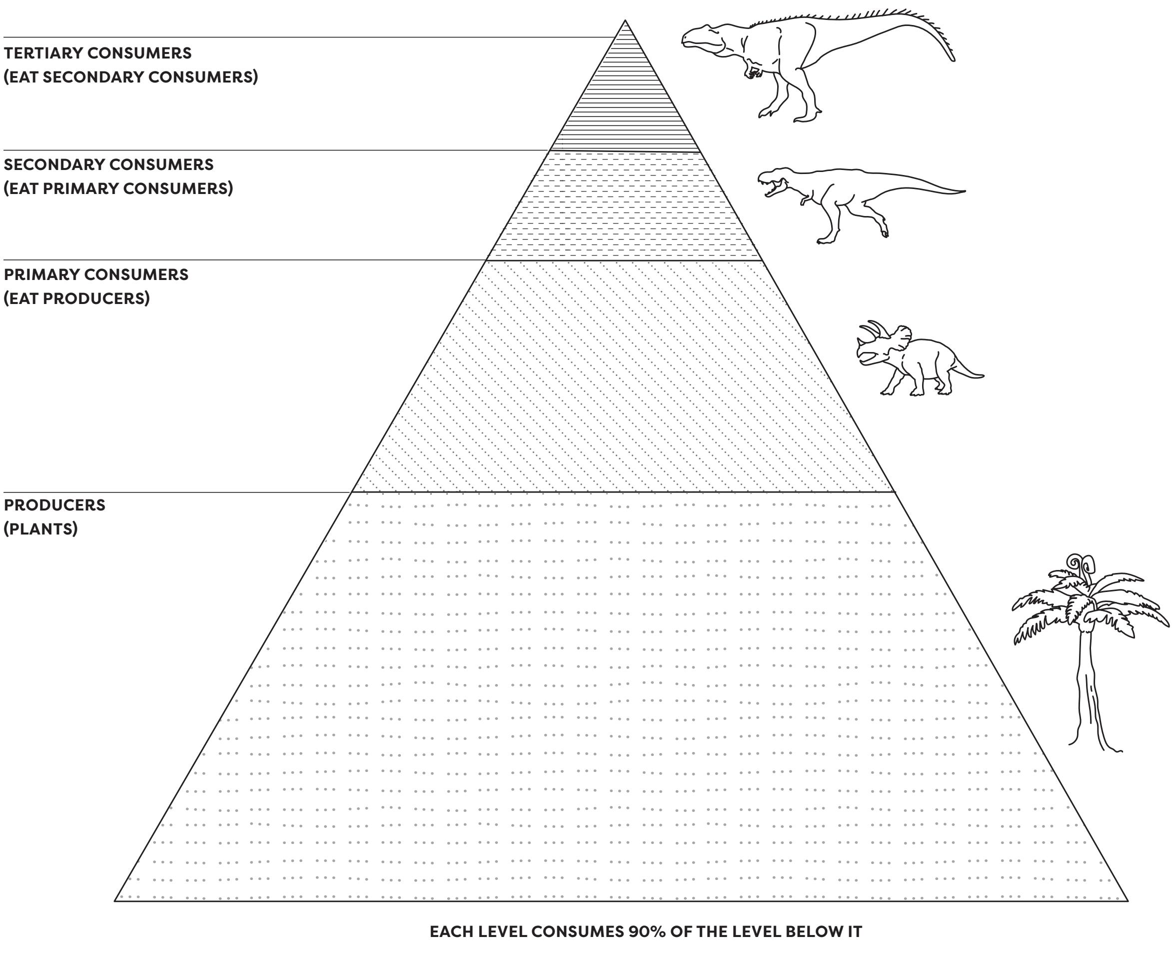
Biologists have tried to work out how much food a large dinosaur would eat each day. They spoke to zookeepers to find out what an elephant eats, which was about 90 lb (40 kg) of plant food a day. If humans eat 2,500 calories per day, that is less than 1 lb (500 g) of food (= 3,500 calories), so the elephant is eating 315,000 calories per day, nearly a hundred times as much as a human eats.

Now, if an elephant weighs 5 tons, and a sauropod dinosaur such as *Diplodocus* weighs 10 tons, did it eat twice as much? The calculations suggest that *Diplodocus* would have eaten about the same amount as a modern elephant, or even less, maybe 66 lb (30 kg) of ferns or horsetails. The reason the dinosaur could eat less was that it had a more efficient system of endothermy (see page 54) and more efficient breathing (see page 64).

DINOSAUR FOOD PYRAMID

Food (energy) passes through an ecosystem usually in the form of a pyramid. There are most primary producers like plants at the base, and these are the food for herbivores.

The carnivores are in smallest numbers because they require a large amount of prey animals (herbivores) for food.



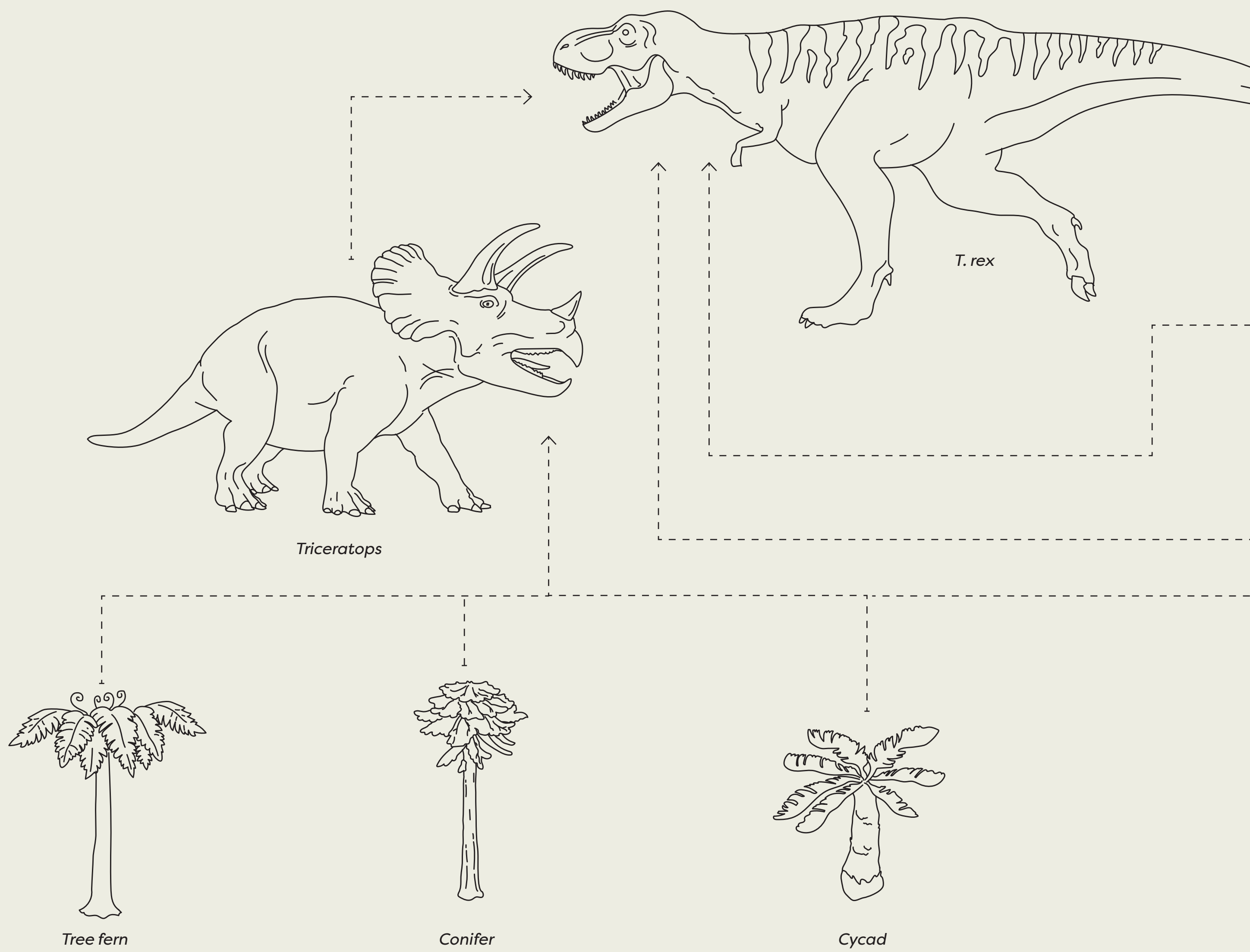
FORENSICS:

MAKING A DINOSAUR FOOD WEB

It might seem fanciful to try to understand how a dinosaurian ecosystem operated, but that is just what paleontologists want to do. First, we know the different species that occur together from their fossils. So, in the food web shown here, from the Hell Creek Formation of Montana, the key dinosaurs are *T. rex*, *Pachycephalosaurus, Triceratops, Ankylosaurus*, and a small raptor such as *Dakotaraptor*. Fossils of all of these have been found sometimes lying close to one another in the same layers of rock, so we are pretty sure they all lived side-by-side in their Late Cretaceous world 67 million years ago.

To start the food web, we draw arrows pointing from food to feeder. We know *T. rex* was the top predator and would eat all the other dinosaurs, so all arrows lead to *T. rex*. There is direct evidence in this case: for example, some *Triceratops* bones show teeth marks made by *T. rex*, and there is a famous specimen of a *T. rex* poop, about 3 ft (1 m) long and full of crushed *Triceratops* bones. That's direct evidence!

Then there are other animals including small mammals, lizards, pond turtles, fish, and insects. There are even many other dinosaurs of hugely differing sizes. We don't show all of



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