BBC Science Focus MAGAZINE

INSTANT GENIUS

INSIDE THEIR MINDS

WHAT JURASSIC PARK GOT WRONG

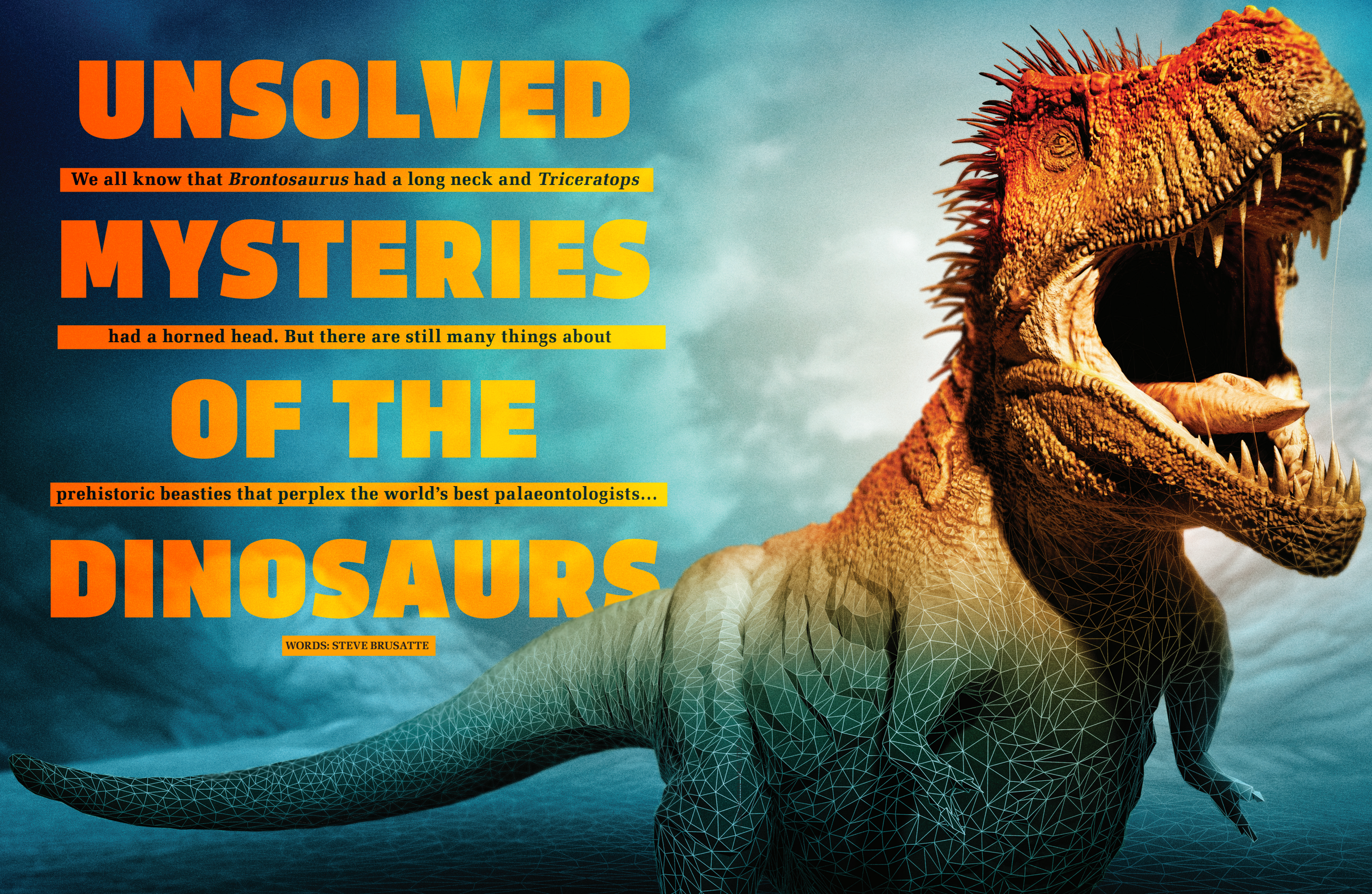
WHAT IF THEY HAD SURVIVED?

DINOSAURS

UNSOLVED MYSTERIES OF THE DINOSAURS

We all know that *Brontosaurus* had a long neck and *Triceratops* had a horned head. But there are still many things about prehistoric beasties that perplex the world's best palaeontologists...

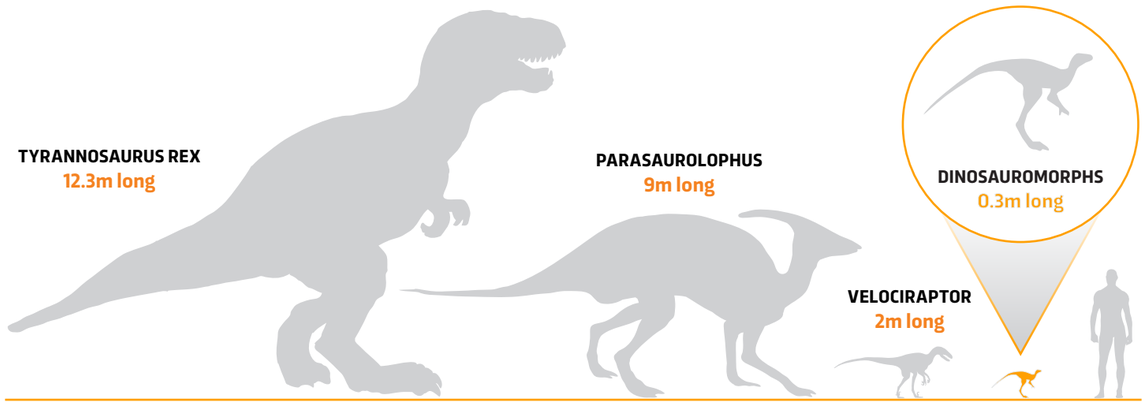
WORDS: STEVE BRUSATTE



Back in November, I was part of a team that described a new dinosaur (pictured). Hailing from southern China and living just a few million years before dinosaurs disappeared, the species would have looked like a deranged bird. It was about the size of a sheep and covered in feathers, with a sharp beak that it probably used to crack open nuts and shellfish. We called it *Tongtianlong* in formal scientific parlance, but gave it the nickname 'Mud Dragon' because its skeleton was found suspended in rock that hardened from ancient mud. It seems like this poor dinosaur got trapped in the muck and died. Then, some 68 million years or so later, its corpse was exhumed by dumb luck as workmen dynamited bedrock while building a school.

It's one of those things that every dinosaur-obsessed child dreams of: getting the chance to discover and name a completely new species. But I'll let you in on one of the dirty little secrets of modern palaeontology. What my Chinese colleagues and I did wasn't that unusual. New dinosaurs are appearing everywhere these days – about 50 new species each year, an average of almost one per week. And this pace shows no signs of slowing, as parts of the world continue to open up to fossil hunters and a fresh generation of scientists, born in the *Jurassic Park* era, come of age. Because of this bounty of new fossils, we now know more about dinosaurs than we do about many modern animals.

But that's not to say that we know everything. Palaeontology is still adventure driven by mystery, and these are some of the biggest riddles that dinosaur hunters are working on today.



WHAT WAS THE FIRST DINOSAUR?

Dinosaurs didn't start out as brutish monsters like *Tyrannosaurus* or behemoths like *Brontosaurus*. They evolved from a group of gangly, cat-sized reptiles called dinosauromorphs, which scuttered around on all-fours in fear of giant amphibians and primitive crocodile relatives called rauisuchians that lorded over the food chain. The first dinosauromorphs started leaving their tracks along the shores of Polish lakes about 250 million years ago, just 1-2 million years after the worst mass extinction in Earth history, when perhaps up to 95 per cent of all species perished in a volcanic hellscape at the boundary between the Permian and Triassic periods.

These dinosauromorphs remained small and rare for many millions of years, then sometime after the volcanoes stopped and the world started to heal, they gave rise to the dinosaurs. The oldest dinosaur fossils come from Argentina and Brazil, and are about 231 million years old. Yet the first dinosaurs probably entered the scene earlier – maybe many millions of years earlier if some scrappy fossils from Africa turn out to be early dinosaurs and not just very advanced dinosauromorphs with similar anatomies and behaviours. The boundary between 'dinosauromorph' and 'dinosaur' is becoming blurrier with each new discovery, but what is becoming clear is that it took tens of millions of years for these first dinosaurs to spread around the world, grow to huge sizes, and become truly dominant. More fossils will surely help, but there isn't a single Rosetta-stone type fossil that could solve the mystery of exactly how dinosaurs rose to power.

Were dinosaurs warm-blooded or cold-blooded?

The old-school image of dinosaurs was not very flattering: crack open a book from the 1950s or 1960s and you'll see drab, scaly, plodding reptiles that look like they're just waiting to go extinct.

That concept went out of favour in the 1970s, as new discoveries like the agile and shockingly bird-like *Deinonychus* proved that dinosaurs were far more dynamic and intelligent than we used to think. Some mavericks even proposed that dinosaurs were warm-blooded like modern birds: they had a constant, high body temperature that they controlled internally through their metabolism, not by basking in the sunshine like an iguana. A few decades later, the evidence is still mixed. The problem is that dinosaurs cannot be observed, so palaeontologists must rely on evidence. Some of it seems convincing: we know from studying their bones that dinos had rapid growth rates, just like modern, warm-blooded animals. But other scientists look at the same evidence and disagree, and some have proposed that dinosaurs had 'mesothermic' metabolisms, somewhere between cold-blooded reptiles and warm-blooded birds. The more we know about how dinosaurs grew, and the more chemical studies of their bones can tell us about their internal body temperatures, the more clarity we will have.

Fast, powerful dinosaurs like *Velociraptor* may have been warm-blooded

PHOTOS: GETTY X4, GETTY/DK IMAGES, ZHAO CHUANG, JUNCHANG LU

WHY DID DINOSAURS HAVE FEATHERS?

In the 1960s, the discovery of *Deinonychus* – long arms, skinny legs, head perched on an arched neck, big claws on the feet – helped solidify the theory that birds evolved from dinosaurs. In the late 1990s, the discovery of thousands of feather-covered dinosaurs in China sealed the deal. But these stunning fossils raised another question: why did feathers first develop in dinosaurs?

Feathers started out as simple, hair-like strands, which probably evolved in some of the most primitive dinosaurs as a way to keep warm. Many dinosaurs retained this basic fluffy coat, but one group of small meat-eaters modified their feathers even further. They got bigger, started to branch, flattened out, and morphed into quill pen feathers like those found on modern birds. These structures lined the arms, and sometimes the legs, forming wings. The reason that some meat-eaters elaborated their feathers was probably for display: to attract mates or intimidate rivals. But with wings, came flight...

The discovery of *Deinonychus*, pictured here, helped us establish that birds evolved from dinosaurs

Flight in small, winged dinosaurs might have evolved by accident

HOW DID THE DINOSAURS LEARN TO FLY?

It all has to do with the wings: no wings, no way an animal can fly. For a long time scientists assumed that wings must have evolved specifically for flight. Evolution must have driven some dinosaurs to turn their hair-like filaments into the more familiar feathers that make a wing, in order for that dinosaur to move through the air. Yet new research suggests that this probably wasn't what happened.

Wings do not show up in the first dinosaurs that started flying. Instead, wings appear in fairly large, ground-dwelling dinosaurs such as the ostrich-like Ornithomimosaurs and beaked omnivores like our Mud Dragon. These dinosaurs were too large and cumbersome to fly. So a new theory is that wings actually originated as display structures – advertising billboards if you like – and only later were repurposed as airfoils. Flight may have evolved by accident as some of these small, winged dinosaurs began jumping between branches or leaping in the air, and suddenly found that their billboards had aerodynamic properties. It is one of the most exciting new hypotheses about dinosaurs.

PHOTOS: GETTY X3, ALAMY, SCIENCE PHOTO LIBRARY X2, AMNH/M ELLISON, RANDY IRMIS

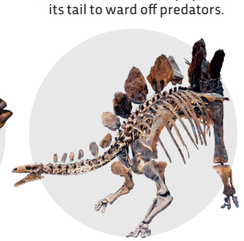
Anchiornis huxleyi was a small, bird-like dinosaur that may have used its feathers to help it glide

DINOSAUR DIVERSITY THROUGH THE AGES

Dinosaurs owned the planet for millennia, evolving into some incredibly iconic species

HERRERASAURUS
Late Triassic
(c. 230 million years ago)
One of the very oldest dinosaurs, *Herrerasaurus* was a fierce predator about the size of a horse. It terrorised other primitive dinosaurs with its sharp claws and teeth.

STEGOSAURUS
Late Jurassic
(c. 150 million years ago)
Stegosaurus has one of the most recognisable profiles of any dinosaur. It probably used the plates on its back as display billboards, and the sharp spikes on its tail to ward off predators.



BRONTOSAURUS
Late Jurassic
(c. 150 million years ago)
The iconic 'thunder lizard', *Brontosaurus*, used its long neck to pluck leaves from high up in the canopy. It must have eaten hundreds of kilograms of plants every day, to fuel its huge body.

MICRORAPTOR
Early Cretaceous
(c. 125 million years ago)
With wings stretching out from its arms and legs, the tiny *Microraptor* looks like a strange species of bird. It is actually a dromaeosaurid, a 'raptor' dinosaur closely related to *Velociraptor*.

PARASAUROLOPHUS
Late Cretaceous
(c. 75 million years ago)
The Late Cretaceous valleys and plains of western North America would have been alive with the bellows of *Parasaurolophus*, a duck-billed dinosaur that used its gaudy head crest to make sounds.

TRICERATOPS
Late Cretaceous
(c. 68-66 million years ago)
Triceratops is famous for its horns, with one sticking up from the nose and one from above each eye. These plant-eaters probably used their horns to wrestle rivals and attract mates.

PACHYCEPHALOSAURUS
Late Cretaceous
(c. 68-66 million years ago)
Pachycephalosaurus had a thick dome of bone on the top of its head. There is debate about what this was for. Was it for display? Or did these plant-eaters butt heads in fights over mates and territory?

TYRANNOSAURUS
Late Cretaceous
(c. 68-66 million years ago)
There is no mistaking the king of dinosaurs, the biggest predator to ever live on land. *T. rex* was a monster: 13m-long, with jaws so strong that it could literally crush through the bones of its prey.

The early bird *Vegavis*, seen here with its voice box highlighted, probably sounded similar to its modern counterparts

WHAT DID DINOSAURS SOUND LIKE?

In films and documentaries, dinosaurs always seem to be roaring. But we don't really know what noises they made, although there are plenty of guesses. What we do know is that some of the first birds that existed alongside dinosaurs probably sounded like today's birds. One spectacular fossil of *Vegavis* (a member of the duck/geese group of birds) includes a voice box that's almost identical to that of modern birds, even though it lived during the Cretaceous. Other scientists have attempted to recreate the sounds of duck-billed dinosaurs by scanning their skulls, building a digital model, and using software from the instrument-making industry to simulate what kind of noises these animals could make. One of these dinosaurs, *Parasaurolophus*, could have passed air through meandering chambers in its gaudy head crest. Simulations show that this air would have been emitted from the nose and mouth as a low frequency rumbling that could change in pitch. In other words, more of a bellow than a roar.

WHAT COLOUR WERE DINOSAURS?

There's something else that feathers can tell us. They unlock the potential to determine what colour dinosaurs were. If you look at modern bird feathers under a high-powered scanning electron microscope, you can see tiny blobs called melanosomes. These are little bag-like structures that hold melanin, one of the main colour-producing pigments in animals. Some melanosomes are globular, others are egg-shaped, and so on. And that's important, because different shapes hold different colour pigments. So if you can identify the shape, you can identify the colour. A few years ago some brilliant palaeontologists realised that you could find melanosomes in particularly well-preserved fossil feathers, like those found coating many of the famous Chinese 'feathered dinosaurs', which were buried rapidly by volcanoes and locked in stone. It turns out that different dinosaurs had all sorts of different melanosomes, which meant they had a variety of different colours. Some were iridescent black like crows, others had ginger feathers, some had rings of colour on their tails like raccoons, and yet others had splotchy colours. Dinosaurs, therefore, had a whole rainbow of hues, just like modern birds.

Perhaps *T. rex* did push-ups to lift itself from the ground after it slept

WHY DID *T. REX* HAVE SUCH TINY ARMS?

Poor *T. rex*, it's the butt of so many jokes about its tiny arms. Its body cries out Arnold Schwarzenegger, but its arms scream Woody Allen. The king of dinosaurs was a 13m-long, meat-crunching machine as an adult, but its arms were no bigger than mine. This has amused, and confused, palaeontologists for decades. But what's important to realise is that while its arms were incredibly short, they were also very muscular. So they must have been doing something. Otherwise, evolution would have just got rid of them, the same way that the hindlimbs of whales disappeared when they were no longer needed. There are many ideas floating around: perhaps *T. rex* did push-ups to lift itself from the ground after it slept, or used its arms as claspers when mating, or simply braced itself against its prey while feeding, for a little extra stability. We still don't know the answer. However, exciting developments in cutting-edge computer modelling software could help us come up with a solution before too long.

No wonder *T. rex* was angry: he couldn't even scratch his belly!

WHY DID DINOSAURS DIE OUT?

And we end with the most enduring mystery of all, the one that has been bickered about ever since the first fossils of giant, extinct reptiles were found in England in the 1820s. Why aren't dinosaurs around today?

Of course, we now know that birds evolved from dinosaurs, so some dinosaurs do persist, but the spirit of the question remains. There is nothing like a *T. rex*, *Triceratops*, or *Brontosaurus* in today's world. They dominated the planet for over 150 million years, but suddenly disappeared from the fossil record 66 million years ago, at the end of the Cretaceous. That's exactly the same time that a 10km-wide asteroid struck what is now Mexico, impacting with the force of over a billion Hiroshima bombs and unleashing an instantaneous apocalypse of earthquakes, tidal waves, wildfires, and hurricane-force winds.

Although palaeontologists still like to argue about what role the asteroid played in the dinosaur extinction, there really isn't much of a mystery left. The asteroid did it, and did it quickly. There are few signs that dinosaurs were struggling before that one fateful moment, when the course of prehistory was changed forever. No dinosaurs, save a few birds, were able to endure the devastation. But some small, omnivorous, furry mammals did. These plucky survivors found themselves in an empty world, and as the planet started to mend, they rapidly evolved into all sorts of new creatures, including the first primates. It was in the ashes of the dinosaurs that our ancestors began their long march.

Dr Steve Brusatte is a palaeontologist at the University of Edinburgh and the author of many books on dinosaurs. His book, *The Rise And Fall Of The Dinosaurs*, was published in 2018.

INSIDE THE MIND OF A DINOSAUR

ILLUSTRATION: MAGIC TORCH

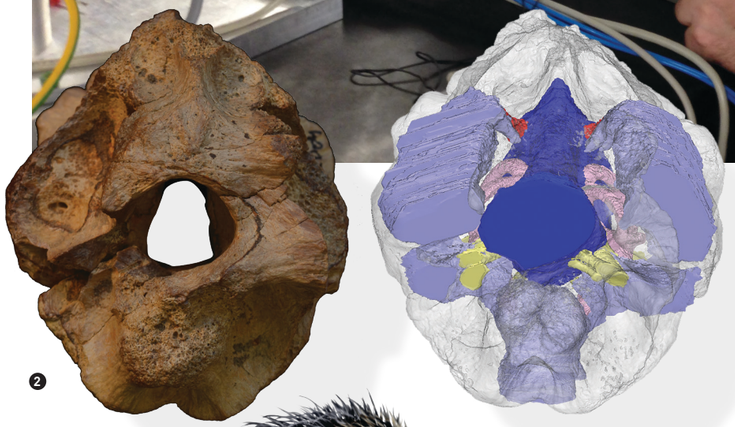
Rather than being slow, lumbering and a bit stupid, dinosaurs were smart and nimble-brained – just ask the palaeontologists who are peering deep inside the fossilised skulls of these prehistoric animals

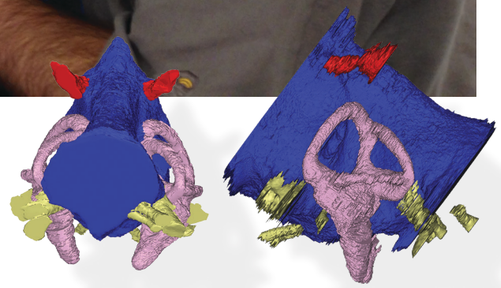
WORDS: DR STEPHEN BRUSATTE

A few years ago, as I loitered in the lobby of a high-rise hotel in Berlin, a man tapped me on the shoulder. In his thick Russian accent, he ushered me into the lift and up to his room. From a duffel bag, he pulled out an ornately coloured cardboard box and handed it to me. I slowly opened the lid. Inside was a grapefruit-sized lump of petrified bone, which I recognised as the back end of a dinosaur skull. "Be careful with the fossil, but be even more careful with the box. This is Soviet box. They don't make them like this any more," he said with a mischievous grin, as he pulled out a bottle of cognac to toast the successful handover.

The man was no secret agent. He was Alexander Averianov, one of Russia's leading palaeontologists and a fellow dinosaur hunter. Nearly a decade before he led an expedition to Uzbekistan's Kyzylkum Desert, a barren expanse that yields some of the world's best Cretaceous-aged fossils. While there, someone on his crew plucked the skull from the sand dunes and safely packed it in the box, where it sat for several years as Averianov tried to make sense of it. He could tell it was the fused mass of bones that surrounded the brain and ear, but wasn't sure what type of dinosaur it belonged to, much less how it might have behaved and interacted with its environment. To figure that out, he would somehow need to see inside the skull: to look at the brain.

This is why he gave the boxed fossil to me, so I could take it to my lab at the University of Edinburgh and analyse it with a computed tomography (CT) scanner. CT scanning – the same technique employed by medical doctors – has become as indispensable to palaeontologists as rock hammers and chisels. By scanning dinosaur skulls, we can literally see inside them and visualise the brains and other rarely fossilised internal structures that powered the intelligence and sensory prowess of these long-dead animals. This helps us understand dinosaurs as living, thinking, moving, evolving creatures, in a way that previous generations never could.

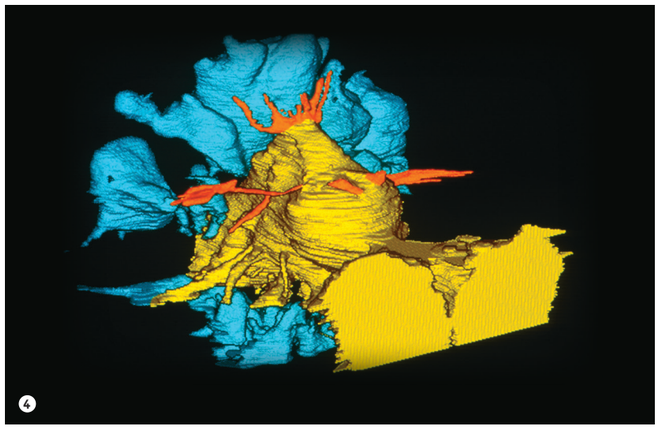




STEVE BRUSATTE X5, TODD MARSHALL, GETTY

SKULL SCANNING

Back in 1912, after the first skeletons of *Tyrannosaurus rex* were discovered, scientists were desperate to understand how such a humongous animal actually lived. The man who named *T. rex*, Henry Fairfield Osborn, knew that the brain held the key. Brain tissue decays quickly after an animal dies, so Osborn conceded that a real dinosaur brain could never survive for millions of years. But perhaps if he could peer into the brain cavity – the space the brain once occupied inside the skull – he could get a sense of the size, shape and dimensions of the brain.



"Be careful with the fossil, but be even more careful with the box. This is Soviet box. They don't make them like this any more"

1 *Timurlengia euotica* had a similar brain to the *T. rex*, but was only about the size of a horse

2 *T. euotica* fossil that was delivered to Stephen Brusatte in a Soviet-era box. From left to right: fossilised braincase (the hole is where the spinal cord enters the brain); CT scan of the braincase, showing the brain, inner ears and sinuses inside the bone; the brain, inner ears and nerves (rear view); brain, inner ears, and nerves (side view)

3 *T. euotica* fossil being examined in a CT scanner

4 CT scan of the brain and sinus cavity of a *T. rex*

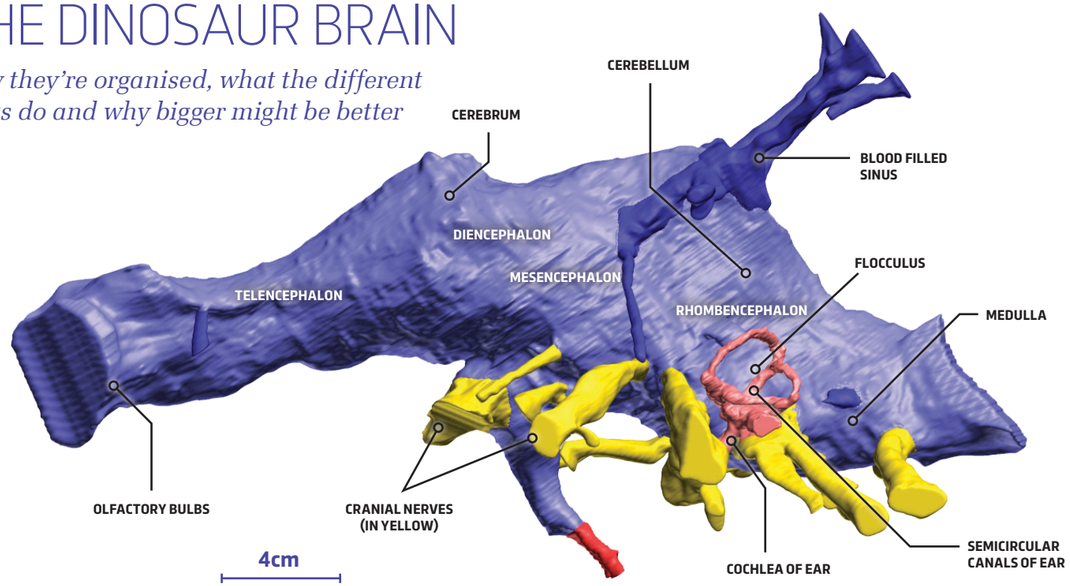
This, however, raised another problem. He could think of only one way to access the brain cavity, so he sawed open a skull of *T. rex*, permanently damaging it – a sacrifice in the name of science.

Not many other scientists had the nerve to cut up their fossils, so for the next several decades there was little research on dinosaur brains. Every once in a while, palaeontologists would find so-called 'natural endocasts': mud or sand that had filled the brain cavity, hardened to stone and then broken free. These were enough for Dr Harry Jerison and Dr James Hopson – two pioneers in the field – to argue that dinosaurs had fairly typical reptilian brains. But they couldn't say much more than that.

Then, beginning in the 1990s, CT scanning changed the game. CT scans are nothing more than X-rays, taken from many angles. If you stick an object in a CT scanner – whether it be a human body or a dinosaur fossil – the X-rays will pass through the object in an orderly manner, and then a computer will combine them into a series of two-dimensional slices. Each slice looks like a traditional X-ray image, of the sort you get at hospital when you break a bone or sprain a ligament. Like the X-ray images we're familiar with, the CT scan slices pick up density differences between materials, so bone shows up as

THE DINOSAUR BRAIN

How they're organised, what the different parts do and why bigger might be better



Dinosaur brains are long and tubular, as can be seen in the *T. rex* brain above. The largest region is usually the telencephalon, comprised principally of the left and right cerebral hemispheres: the seat of intelligence and sensory functions. At the front of the telencephalon are the olfactory bulbs that control the sense of smell, and behind it are the optic lobes of the diencephalon that power vision. A small midbrain region (mesencephalon) separates the diencephalon from the hindbrain (rhombencephalon). The rhombencephalon is further divided into the cerebellum, which plays a role in motor function, and the medulla, from which emerge the cranial nerves that control breathing, heart rate, blood pressure and other involuntary functions. A lobe of the cerebellum called the flocculus emerges laterally; it helps regulate eye, neck and head movements.

On the sides of the brain are the inner ears, which consist of the pretzel-shaped semicircular canals that are filled with fluid to help regulate balance and head stabilisation. Beneath are the long cochlea, which control hearing. A number of air-filled sinuses emanating from the inner ear surround the sides of the brain, possibly helping to cool the brain or to enhance hearing. Other blood-filled sinuses cushion the sides and top of the brain.

The size of the brain can be used to estimate intelligence. Although measuring intelligence is riddled with uncertainties, there is a straightforward measure to roughly compare the intelligence of different animals: the encephalisation quotient (EQ). It's basically a measure of the relative size of the brain compared to the size of the body. Large animals usually have larger brains than smaller animals, even if they're not more intelligent, so the larger the EQ, the bigger the brain is relative to its expected value for the animal's size, and thus the more intelligent the animal is considered to be.

a different greyscale colour to air or sand or mud. The series of CT slices is essentially a flipbook of images, which specialised software can assemble into a digital 3D model of the entire object that was scanned. Thus, the scan allows palaeontologists to see inside a fossil without cutting it open, the same way it permits a doctor to visualise the details of our internal anatomy without needing to do surgery.

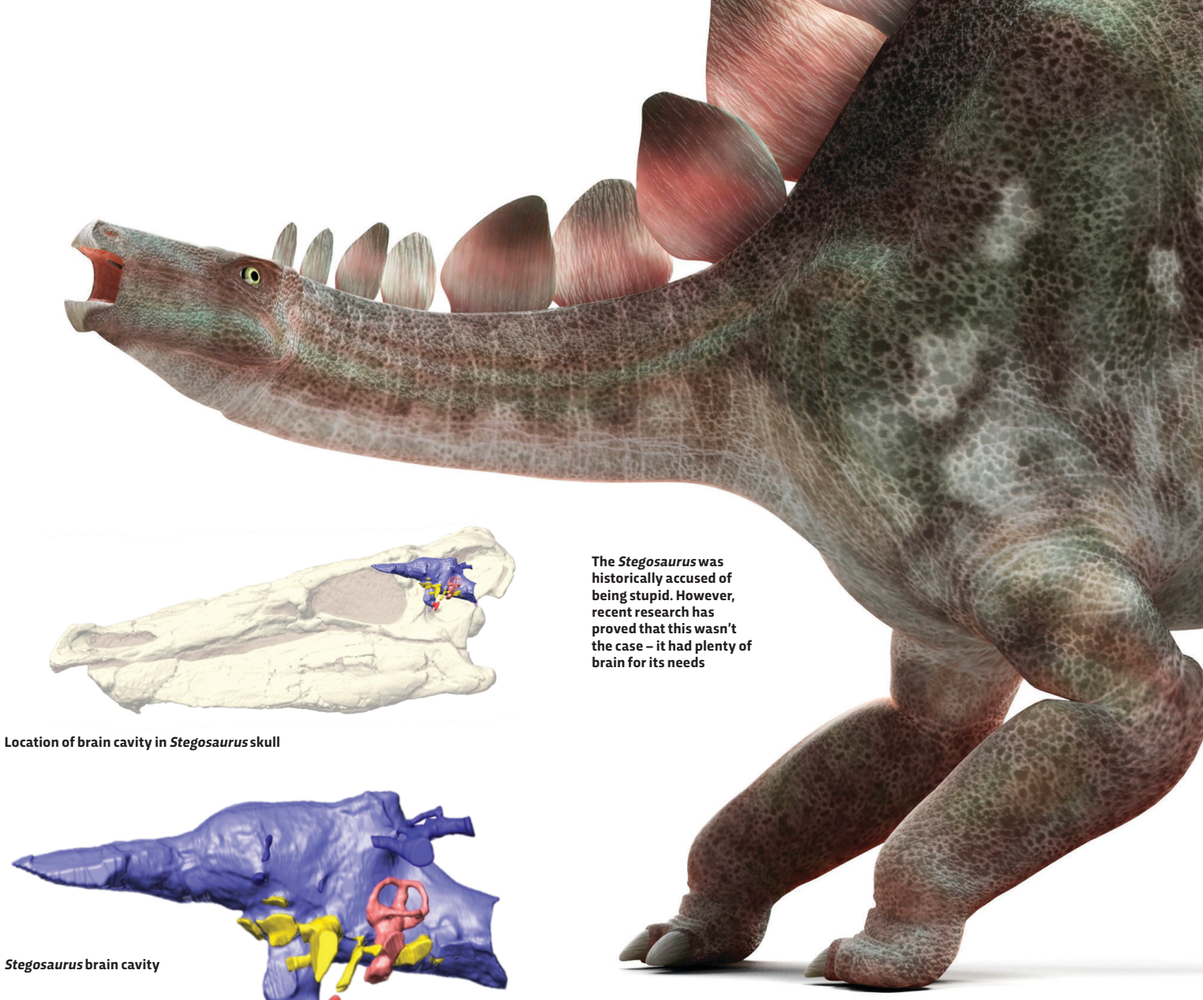
CT scanning revolutionised palaeontology just as it did medicine. Now, scientists can simply put dinosaur skulls in a scanner and generate digital models of the filled-in brain cavity, inner ear, blood vessels, nerves and sinuses. It's non-invasive, relatively inexpensive and can be done using the same equipment found in almost any hospital. Nowadays, palaeontologists have become so accustomed to CT scanning that many of us have bespoke scanners in our labs or even use synchrotron particle accelerators to generate the high energies needed to scan sub-micron-sized details of the tiniest fossils.

ALL BRAWN, NO BRAIN?

The oldest dinosaurs, which lived during the Triassic Period (around 230 million years ago), had small and fairly primitive brains that were not too different from those of other reptiles. Some plant-eating dinosaurs retained these rudimentary brains, including the famous plate-backed *Stegosaurus*, which lived during the Jurassic Period (around 150 million years ago).

Stegosaurus was a popular punchline in the dinosaur books that I read as a kid, with its supposedly

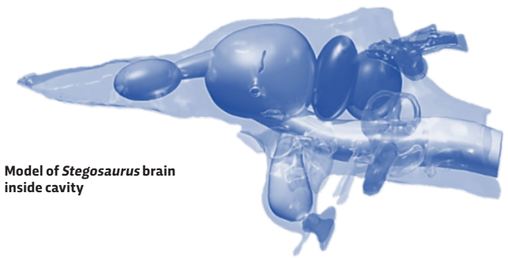
STEVE BRUSATTE, ASHLEY MORHARDT, GETTY



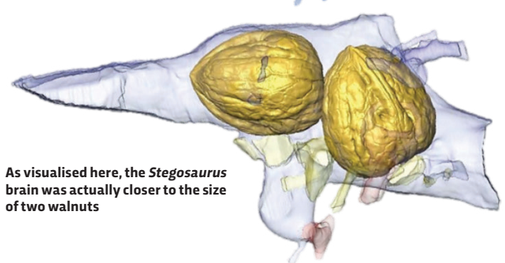
The *Stegosaurus* was historically accused of being stupid. However, recent research has proved that this wasn't the case – it had plenty of brain for its needs

Location of brain cavity in *Stegosaurus* skull

Stegosaurus brain cavity



Model of *Stegosaurus* brain inside cavity



As visualised here, the *Stegosaurus* brain was actually closer to the size of two walnuts

'walnut-sized' brain exemplifying how dinosaurs were lethargic dullards that were poorly suited to their environments. As with so many cherished stories about dinosaurs, this turns out to be mostly wrong. Dr Ashley Morhardt, a palaeontologist at Washington University in St Louis, Missouri, scanned a *Stegosaurus* skull and found that the brain is indeed small for a dinosaur, but it was closer in size to two or three walnuts. No doubt, this was more than enough brainpower for *Stegosaurus* to survive in the rough-and-tumble world of the Jurassic. Even the dullest dinosaurs were much smarter than popular culture gives them credit for.

Another group of herbivores modified the brain and inner ear to fit their lifestyles. Sauropods – the group of pot-bellied, long-necked behemoths that included *Diplodocus* and *Brontosaurus* – were the biggest animals to ever live on land. The earliest sauropods were dog-sized critters such as the Triassic's *Saturnalia*, which had a small brain with big flocculus lobes that permitted fine-tuned head,

neck and eye movements. As sauropods got bigger and started walking on four legs, the flocculus got smaller, as did the semicircular canals of the ear, which help regulate balance. It seems as if sophisticated locomotion was becoming less important to these animals as they devoted more time and energy to eating the huge quantities of leaves and stems needed to power their ever-growing metabolism.

There's something else peculiar about the hugest sauropods: different species had inner ears oriented in different directions. It's widely known that in living animals the lateral semicircular canal of the ear is held in a horizontal plane when the animal employs a 'neutral' head posture. A study by University of Chicago palaeontologist Dr Paul Sereno found that some sauropods, such as the spatula-toothed *Camarasaurus* stuck their heads out nearly straight when in this neutral posture, but others like *Nigersaurus* pointed their heads downwards. This suggests that *Camarasaurus*-type sauropods lifted their necks high into the air, whereas *Nigersaurus* was more like a vacuum cleaner that sucked up plants near the ground. Sauropods were evidently changing their sensory systems to allow them to feed in different styles and on different types of plants, which is probably one reason why so many species were able to coexist in the same environments, as they weren't competing with each other. Sensory changes, therefore, were one of their keys to success.

WHO'RE YOU CALLING FEATHERBRAINED?

Meat-eating theropods, such as *T. rex* and *Velociraptor*, are celebrated for their sharp teeth and killer claws, but their arsenal of predatory weapons also included keen intelligence and senses. The smartest dinosaurs of all were small, feathered species closely related to birds, such as *Velociraptor*, *Troodon* and *Zanabazar*.

Dr Amy Balanoff of Johns Hopkins University has built her career studying the brains of dinosaurs, meticulously scanning fossil after fossil, including

ABOVE LEFT: **By studying the brain and ears of *Nigersaurus*, scientists established that this sauropod fed on plants near the ground**

ABOVE: **In the Gobi Desert, Dr Mark Norell has excavated a lot of Cretaceous-aged skulls, many of which are from fast, intelligent dinosaurs that have brains extremely similar to ancient birds**

many stellar Cretaceous-aged skulls (around 75-80 million years old) that Dr Mark Norell, a palaeontologist from the American Museum of Natural History, excavated from the Gobi Desert. These feisty, fast-running predators had, proportionally, the largest brains, relative to body size, of any dinosaurs. This is largely due to their enlarged cerebrums and it means that they were probably among the most intelligent of all dinosaurs. Not only that, but their brains are essentially indistinguishable in size and shape from the brains of the oldest birds, which may indicate that some of these *Velociraptor*-grade theropods were capable of flight. Work by University of Calgary palaeontologist Dr Darla Zelenitsky has also shown that the 'raptor' dinosaurs had proportionally huge olfactory bulbs relative to most other theropods, suggesting they used a sharp sense of smell to seek out their prey. Whether they were capable of the kind of cunning depicted in *Jurassic Park* is a matter of speculation, however!

"Tyrannosaurus rex's brainpower and sensory acumen ensured that it was the biggest, baddest predator that ever lived"

As fearsome as a pack of *Velociraptors* would have been, no theropod eclipses the King of Dinosaurs: *T. rex*. Over a century ago, Osborn's sawed-up skull hinted that *T. rex* had a fairly large brain and more recent CT work by Dr Larry Witmer of Ohio University confirms it. In fact, not only was *T. rex* roughly as intelligent as a chimp, but it had enormous olfactory bulbs that imparted a strong sense of smell, elongate and looping inner ear canals that coordinated rapid eye movements and quick reflexes, and an elongate cochlea that could hear low-frequency sounds. If a 13-metre-long, 7-tonne, bone-crunching predator wasn't scary enough, its brainpower and sensory acumen ensured that *T. rex* was the biggest, baddest predator that ever lived.

This raises a question: how did *T. rex* evolve these features? The boxed-up skull that Averianov gave me in Berlin provides the answer. When I brought the skull to Edinburgh, I handed it over to Dr Ian Butler, my geochemist colleague who hand-built his own CT scanner, and my student Amy Muir, a maestro at reading CT scans. Our visualisation of the brain showed that the skull – which we later named as a new species, *Timurlengia euotica* – had the characteristic elongate and peaked brain of *T. rex*, with a long cochlea. But *T. euotica* was much smaller, only about the size of a horse, and lived about 25 million years before *T. rex*. Thus, the ancestors of *T. rex* evolved big brains and keen senses before they developed huge body size. So tyrannosaurs got smart before they got big – and getting smart was probably what allowed them to rise to the top of the food chain, grow to monstrous sizes and become the ultimate dinosaur success story.

GETTY X4, AMNH/S GOLDBERG

DINOSAURS AMONG US?

WORDS: DR DARREN NAISH

There is scientific value in using modern animals as analogues for those that went extinct millions of years ago. But it has to be done carefully, and any inferences made about dinosaurs' lives and behaviours based on those of living species come with a plenty of caveats. Palaeontologists limit the species they're analysing using a technique called 'phylogenetic bracketing', where they look at the evolutionary tree to which the extinct animal belongs and the existing animals that are closely related to it. The result is that if we wish to know about any aspect of dinosaur biology or anatomy not preserved in fossils, we can look to its closest living relatives for clues.

Zip it

It's impossible to know what sounds dinosaurs made as their noise-making organs have not been preserved. But both crocodilians and birds (which share a common ancestor with dinosaurs) possess a larynx. Crocodiles and large birds, such as emus, use this organ to make deep, rumbling sounds, so it's possible that dinosaurs did too. But rather than open their mouths or beaks to let out these noises, they use their puffed-out necks or chests as reverberating chambers. So even if *T. rex* did roar, chances are it didn't do it with a wide-open mouth.

Chicken dance

Modern birds are different from theropods like *T. rex* and *Velociraptor* as they have substantially shorter tails, wider hips and rely on their knees more than their hips to move their legs. In an effort to compensate for these differences and better understand the locomotion in ancient theropods, scientists attached long, tail-like prostheses to the rear ends of chickens. The birds learnt to walk with more of a 'dinosaur gait', proving that birds still have this ability even if aspects of their proportions undergo change.

Claw-some

Dromaeosaurids, the theropod family that includes *Velociraptor*, often had large, curved and pointed claws on their feet that were held up off the ground. It was thought that the animal would stand on one leg and kick at a prey animal to disembowel it using its claw. But this technique is not used by any modern predator. By examining the hunting behaviour of owls, hawks and eagles, which have similarly clawed feet, researchers have come to the conclusion that these dinosaurs used their claws to pin down prey while attacking it with their mouths.

Dr Stephen Brusatte is a palaeontologist at the University of Edinburgh and is the author of many books on dinosaurs. His newest book, *The Rise And Fall Of The Dinosaurs*, was published in May 2018 (£20, Macmillan).

JURASSIC PARK

***When the Jurassic Park was released in 1993, it presented a new image of dinosaurs far different from the plodding dullards of old films and textbooks. Much of what we've learned over the past quarter of a century corroborates this image: dinosaurs were active, energetic and intelligent creatures that were closely related to birds. But palaeontologists have learned a lot about dinosaurs over the last few decades, as a result of hundreds of new fossil species being discovered and the introduction of cutting-edge technologies like CT scanners and computer animation software. Here are five things that we now know were incorrect about the dinosaurs in* Jurassic Park…**

1) LACK OF FEATHERS

The scaly *Jurassic Park* dinosaurs look quite a bit like oversized lizards. This is how dinosaurs used to be depicted in children's books and museum exhibits, and it was still the current thinking in 1993. But then, in 1996, everything changed. A farmer in Liaoning, China, discovered the skeleton of a dinosaur covered in feathers. Hundreds more soon followed. These feathered dinosaurs showed once and for all that birds evolved from dinosaurs. It also proved that many dinosaurs had feathers, including small carnivores like *Velociraptor*, bigger meat-eaters like *T. rex*, and even some plant-eating dinosaurs. A lot of palaeontologists now think that *all* dinosaurs had some type of feathers. Small, wispy 'protofeathers' (hair-like precursors of modern bird feathers) were added to some of the dinosaurs in some of the later *Jurassic Park* films, but in the most recent *Jurassic World* the dinosaurs were scaly once again.

2) DULL SKINS

Not only are the *Jurassic Park* dinosaurs scaly, but they are mostly drab in colour, with green, brown or earth-toned skin that also appears reptilian in style. Not all dinosaurs would have looked like this, however. In the late 2000s, a graduate student called Jakob Vinther figured out how to tell the colour of dinosaurs. He found that if you put well-preserved feathers or skin under a scanning electron microscope, you can see pigment-bearing vessels called melanosomes. We know from modern animals that different-shaped melanosomes correspond to different colours: sausage-shaped ones make black, meatball-shaped ones a rusty red, and so on. Through this technique, we now know that dinosaurs came in all sorts of fantastic colours, just like today's birds. Some were black or white, others brown or ginger, some were multicoloured or iridescent, and one small carnivore called *Sinosauropteryx* even had a ringed tail of red and white bands.

SHUTTERSTOCK X4

3) SPEEDY *T. REX*

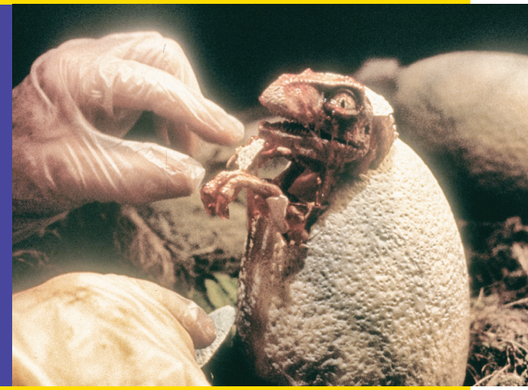
A famous scene in *Jurassic Park* shows a bloodthirsty *T. rex* chasing down a jeep moving at highway speeds. This was a reasonable assumption to make in 1993, as the long and muscular legs of *T. rex* looked like they were capable of great bursts of speed. Computer modelling studies, however, have revealed something quite different. Work by Dr John Hutchinson in the early 2000s found that *T. rex* would have needed laughably huge leg muscles – making up an absurdly impractical 86 per cent of total body mass – to move at more than 32km/h (20mph). And then, even if this were somehow possible, the massive seven-tonne bulk of *T. rex* would have made it liable to tip over when running, like a truck taking a corner too quickly. The modern image of *T. rex* is an animal that probably maxed out at about 16-24km/h (10-15mph).

4) YOU'RE SAFE IF YOU'RE STILL

There's something else that *Jurassic Park* got wrong about *T. rex*. Recall the scene where the frightened youngster is told to stand still, because the *T. rex* is incapable of sensing prey that doesn't move? New research shows that this advice would have proven deadly. CT scans reveal that *T. rex* had a large brain, with huge olfactory lobes that powered a highly sensitive nose, and an inner ear with a long cochlea that could hear a wide range of sounds. Furthermore, the eyes of *T. rex* faced partially forward, permitting binocular vision with keen depth perception. Add this all together and you get a smart animal with sharp senses that probably would have seen, smelled and heard the little boy. These superpowers were as much of a part of *T. rex*'s predatory arsenal as its claws and teeth.

5) CLONES FROM FOSSILS

The science of dinosaurs has progressed at an exponential pace over the last few decades, but there are still many things we don't know. One of the great hopes of the *Jurassic Park* era – and the premise of the entire movie franchise – was that dinosaurs could one day be cloned from fossilised remnants of their DNA. Many palaeontologists have been looking, but as yet, not one fragment of the dinosaur genome has been recovered. And maybe it never will: DNA degrades quickly once an animal dies, so preserving even small amounts for millions of years may be purely in the realm of sci-fi. Still, palaeontologist Dr Mary Schweitzer and her team have defied the odds and identified bits of dinosaur soft tissue like proteins and blood vessels, so maybe DNA is next…



To listen to an episode of ***In Our Time*** about feathered dinosaurs, visit **bbc.in/2DX3GMy**

WHAT IF THE DINOSAURS HAD SURVIVED?

If the dinosaurs hadn't been wiped out in a mass extinction 66 million years ago, the world would look very different today

Words: John Pickrell Illustrations: James Gilleard

Artist's impression of how dinosaurs could have looked, if they had survived

Around 66 million years ago, a 14km-wide asteroid smashed into our planet. An estimated 15 billion tonnes of soot spread through the atmosphere, creating one long night that lasted several years and made photosynthesis all but impossible. It heralded an endless winter that saw average temperatures fall by as much as 28°C. These are the conditions that the few wretched creatures that survived the initial impact had to endure – not to mention the earthquakes, tsunamis, wildfires and volcanic eruptions that swiftly followed in its wake.

Around three-quarters of all species went extinct and no animal bigger than a Labrador dog survived. But according to researchers at the University of Texas, things could have been very different. They reported findings that had the asteroid struck Earth just a few minutes earlier, it would have hit the deep ocean rather than the shallow sea of the Yucatan Peninsula in present-day Mexico.

Had that been the case, then the damage would have been more localised. Some of the dinosaurs far from the impact site might have survived, and the world would be a different place today. In our own history, only the feathered theropod dinosaurs (a group of bipedal dinosaurs) we know as birds made it through the calamity, but how would things have turned out if their larger relatives had joined them? Would dinosaurs still be alive today and could mammals such as humans have evolved? What would our world look like if we shared it with the descendants of animals like *T. rex* and *Triceratops*?

"I'm sure a fairly nice diversity of non-avian dinosaurs would still be here," says Dr Stephen Brusatte, a palaeontologist at the University of Edinburgh. "If there was no sudden, catastrophic shock of the asteroid, I really don't see anything that's happened since – whether it was the spread of grasslands; changing ocean currents; the separation of Antarctica from South America, which caused a cold snap; or the more recent Ice Ages – that would have knocked off the dinosaurs."

"Given that arms were non-critical for hunting, it's possible a tyrannosaur could have been armless"

Over the years many have tried to imagine what kind of creatures dinosaurs might have evolved into had they survived. The most famous attempt is a 1988 book called *The New Dinosaurs: An Alternative Evolution*, by Scottish geologist and author Dougal Dixon. For this magnificent work of speculative zoology, Dixon conjured up creatures such as the 'cutlasstooth' – a pack-hunting, sabre-toothed predator from South America; the 'cribrum' – a flamingo-like, filter-feeding theropod from Australia; and the 'gourmand' – a relative of *T. rex* that lost its front limbs entirely and developed a distensible jaw to allow it to rapidly swallow prey whole, much like a snake.

Perhaps this last idea isn't entirely wide of the mark. Dr Tom Holtz, an expert on theropod dinosaurs at the University of Maryland in the US, says that both tyrannosaurs and abelisaurs, the two types of big meat-eater present in the Late Cretaceous, are notable for their tiny forelimbs. "Given that arms were non-critical for hunting, it's possible that a Cenozoic [current geological era] tyrannosaur could have been armless," says Holtz.

THE DINOSAURS THAT COULD HAVE BEEN

If the dinosaurs had continued to evolve, all kinds of new body forms might have developed

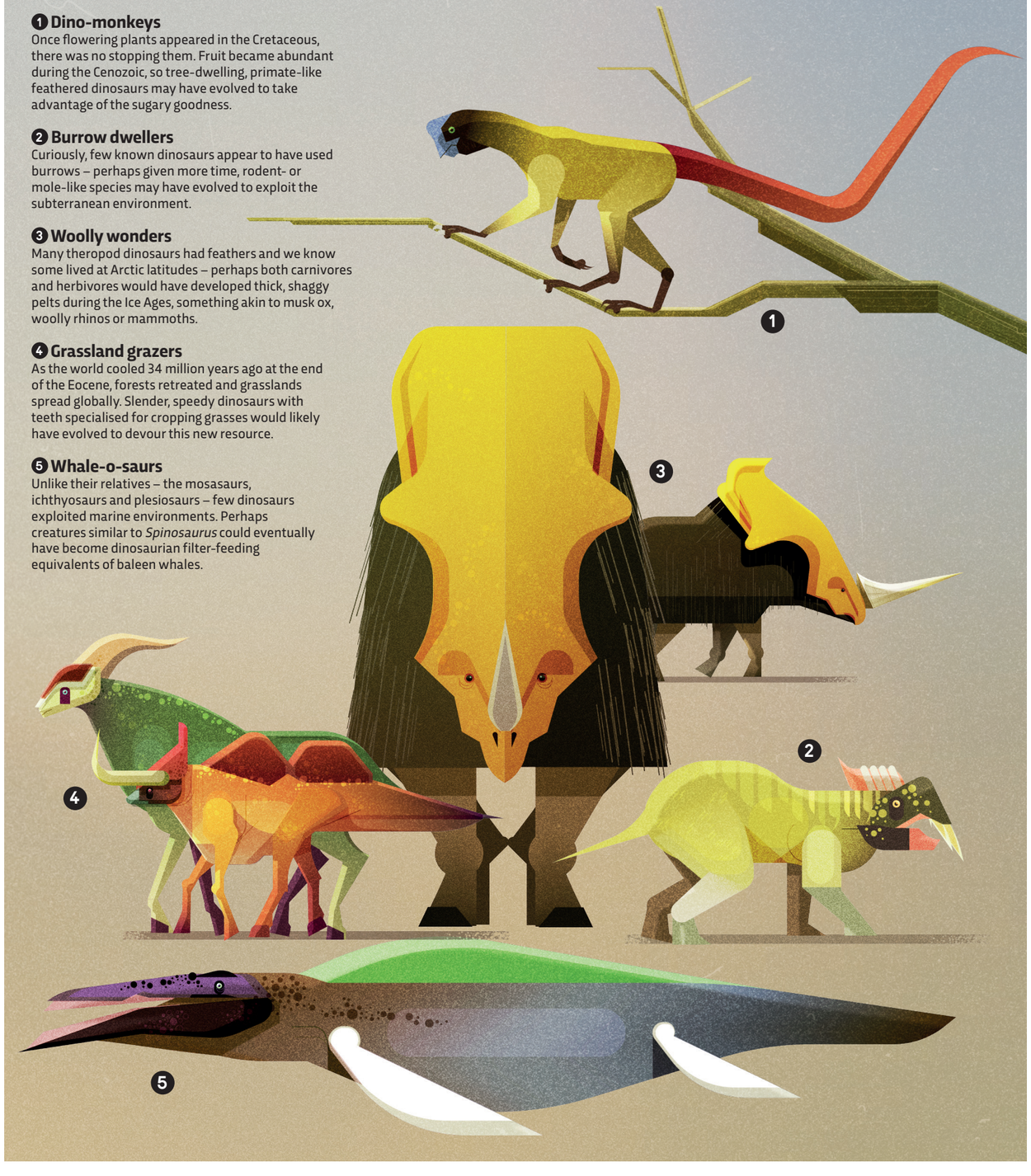
1 Dino-monkeys
Once flowering plants appeared in the Cretaceous, there was no stopping them. Fruit became abundant during the Cenozoic, so tree-dwelling, primate-like feathered dinosaurs may have evolved to take advantage of the sugary goodness.

2 Burrow dwellers
Curiously, few known dinosaurs appear to have used burrows – perhaps given more time, rodent- or mole-like species may have evolved to exploit the subterranean environment.

3 Woolly wonders
Many theropod dinosaurs had feathers and we know some lived at Arctic latitudes – perhaps both carnivores and herbivores would have developed thick, shaggy pelts during the Ice Ages, something akin to musk ox, woolly rhinos or mammoths.

4 Grassland grazers
As the world cooled 34 million years ago at the end of the Eocene, forests retreated and grasslands spread globally. Slender, speedy dinosaurs with teeth specialised for cropping grasses would likely have evolved to devour this new resource.

5 Whale-o-saurs
Unlike their relatives – the mosasaurs, ichthyosaurs and plesiosaurs – few dinosaurs exploited marine environments. Perhaps creatures similar to *Spinosaurus* could eventually have become dinosaurian filter-feeding equivalents of baleen whales.



“You can’t underestimate the importance of that extinction really hitting the reset button for mammals and clearing the playing field”

The beginning of the Cenozoic Era (which spans the period from 66 million years ago until the present day) might essentially have been an ecological extension of the Late Cretaceous. Various creatures such as titanosaur sauropods (huge, long-necked dinosaurs like *Argentinosaurus*), hadrosaurs (duck-billed dinosaurs like *Edmontosaurus*), ceratopsians (horned, beaked dinosaurs like *Triceratops*), and predators such as the tyrannosaurs would still have remained common.

But as we head further from the Cretaceous towards the present day, there would likely have been significant changes, says Dr Andy Farke at the Raymond M. Alf Museum of Paleontology in Claremont, California. “If dinosaurs were still around today they’d be pretty different to what we think of at the end of the age of the dinosaurs – things like *T. rex* and *Triceratops*,” he argues. “You might still recognise them as a dinosaur, but who knows what kind of body shapes and body plans might have come up in the past 66 million years.”

Many of the mammals with which we’re familiar might not have had the opportunity to evolve. “You can’t underestimate the importance of that extinction 66 million years ago in really hitting the reset button for mammals and clearing the playing field,” adds Farke.

TREE HUGGERS

Already in the Cretaceous there were numerous fluffy, feathered theropods scampering in the trees. Assuming that flowering plants continued to spread and thrive as they did in our history, then could primate-like dinosaurs have specialised to take advantage of the fruit they produced? Prof Matthew Bonnan, a palaeobiologist at Stockton University in New Jersey, argues that primates evolved large, forward-facing eyes with colour vision to forage for fruit.

“Is there a connection between being frugivorous [fruit-eating] and having a larger brain? We don’t know, but one could imagine arboreal dinosaurs that formed a co-evolutionary relationship with flowering plants by eating their fruits and dispersing the seeds,” he says. “Whether these fruit-eating dinosaurs would have evolved complex social groups like primates is pure speculation.”

Other ecological spaces little explored by dinosaurs were aquatic environments. “In mammals we’ve seen a return to the sea, in several different iterations,” says Farke. “We’ve had things like whales and manatees that have gone back into the oceans, and things like otters that spend a lot of time in the water. It’s cool to think about what dinosaurs could have looked like if they’d gone in a cetacean direction.”

But if their giant marine reptile relatives – the mosasaurs and plesiosaurs – had survived, then dinosaurs might have found it hard to get a foothold.

There could also have been other consequences of dinosaurs and their reptilian relatives, such as the flying pterosaurs, not petering out at the end of the Cretaceous. Although birds co-existed with dinosaurs for a long time in the Cretaceous, their diversity was low compared to today. “Modern bird groups underwent an explosive radiation after the mass extinction, maybe because pterosaurs went extinct and opened up new niches,” says Dr Victoria Arbour, a palaeontologist at the

Certain dinosaurs might have gone back into the oceans, like the manatee did

PHOTO: GETTY

If dinosaurs had survived into the Ice Ages, could they have developed thick pelts like modern musk ox?

Royal Ontario Museum in Toronto. "Without the mass extinction, maybe birds wouldn't be as diverse and successful as they are today, and maybe we wouldn't have things like songbirds, parrots, hawks, or hummingbirds at all."

Most experts seem to agree that the largest land mammals such as elephants, mammoths, giant relatives of rhinos and sloths, and perhaps even horses and giraffes, probably couldn't have evolved if large dinosaurs had remained to occupy the niches they came to fill.

But perhaps smaller mammals such as rodents, bats and primates would have been just as successful. If that had been the case, then some of those primates could have climbed down from the trees onto the grasslands and savannahs that eventually replaced the thick forests of the Cretaceous, and evolved into hominids, as our ancestors did.

"If we speculate that humans had evolved alongside dinosaurs, then they probably would have been able to co-exist," says Farke. "Humans already evolved in ecosystems that had large land animals and predators. We probably would have done okay."

"Unarmed, solitary humans are still easy targets for large predators like bears and lions," agrees Arbour. "But overall humans are pretty good at surviving alongside large, dangerous animals."

"If we speculate that humans had evolved alongside dinosaurs, then they probably would have been able to co-exist"

CENOZOIC EXTINCTION

Dinosaurs might not have been so lucky though, as humans seem to have a special skill for killing off large animals. Perhaps the biggest dinosaurs would have gone the way of the mammoth and the dodo. "Humans are really good at extinguishing megafauna – through hunting, climate change or habitat destruction," Arbour says. "Dinosaurs in the 21st Century, just like modern animals, would probably have reduced populations and face the threat of extinction."

Big dinosaurs would perhaps only persist in protected reserves, such as national parks and wildlife refuges – modern-day equivalents of *Jurassic Park*.

PHOTO: GETTY

DOMESTICATED DINOSAURS

Had dinosaurs survived, might we have used them for labour and food, or hunted them as trophies?

In the cartoon *The Flintstones*, Fred Flintstone works as a 'bronto crane operator', riding a sauropod that does the heavy lifting in a quarry. Yet it seems unlikely that we would ever have been able to persuade dinosaurs to work for us in agrarian societies – as humans did with oxen and horses. "Given the brainpower of some of these dinosaurs, I can't imagine that a lot of them would be in the realm of things that would domesticate easily," says palaeontologist Dr Andy Farke.

But there may have been other ways that humans could have exploited dinosaurs.

"Animals that have been domesticated by humans are often those that have group social structures like wolves, caribou and cattle," says palaeontologist Dr Victoria Arbour. "For dinosaurs, herding species like ceratopsians and hadrosaurs might have been good candidates for cattle analogues. There's less evidence for social behaviour in small carnivores, but perhaps some little predatory, feathery theropods might have filled the spots in our homes reserved for dogs and cats today."

Had we exploited some of these larger herbivores to toil in our fields, then surely we would have hunted and farmed some for meat too? This begs the question: what would dinosaur meat have tasted like? Of course, if you eat chicken or turkey today, then you are already eating theropod dinosaur, but the flesh of these sedentary domesticated creatures is a poor analogy for *T. rex* meat – a better one might be emu or ostrich, which is packed with lean muscle due to the animals' sprinting abilities.

"Just as with modern farming there'd probably be the whole thing with wanting to get organically raised or free-range dinosaur meat – or corn-fed *Triceratops*," quips Farke.

Ostriches are farmed today, so some of the fast, ostrich-like ornithomimid dinosaurs, such as *Gallimimus* (famous from the stampede scene in *Jurassic Park*), could have populated ranches in the same way.

Battery farms of egg-laying dinosaurs could also have been a possibility. "The glorious thing about dinosaurs is that they grew very quickly," says Farke.

Today, there are certain types of wealthy gun-lovers who will pay significant sums of money to shoot lions, rhinos and giraffes on private game reserves. Therefore, had dinosaurs survived to the present, then they would surely be the ultimate in big game. Horned dinosaurs, duckbills and even carnivores like *T. rex* could have been targets, argues Arbour. "Big ceratopsians, hadrosaurs and theropods would probably be highly sought after for trophy hunting," she says.

JURASSIC BARK?

A *T. rex* would probably make a terrible house pet (just think of the litter tray!). But could some smaller species have made more fitting companions?

Microraptor

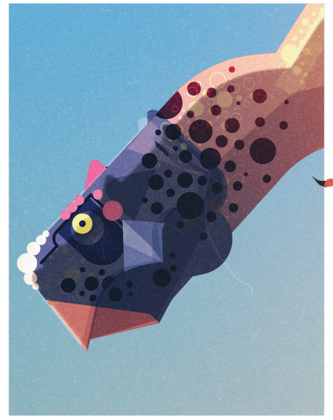
Dark and iridescent plumage, with large flight feathers on its hind and forelimbs. Likes to preen, nap and observe everything with its hawk-like watchful eyes.

SIZE: One of the tiniest dinos at less than 1kg in weight and about 80cm in length.
PROS: Has four wings of awesomeness. It's intelligent and responds well to commands.
CONS: Can attempt to disembowel the cat with its sickle-shaped second claw; requires falconry hood during initial training.

Sinosauropteryx

The first known feathered dinosaur, discovered in 1996. Has fluffy ginger plumage and enjoys scratches and strokes. Likes to chase toys in lieu of fast-moving prey.

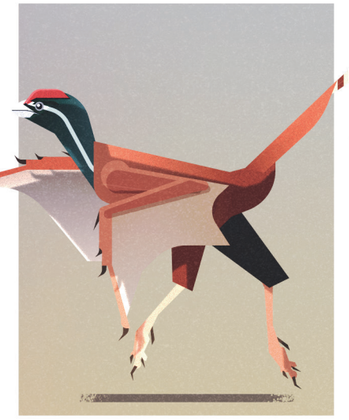
SIZE: A metre in length, including the long tail. But it's very dainty, weighing just 0.5kg.
PROS: Loves to snuggle. Has fetching ginger-and-white tail stripes.
CONS: Can be neurotic and restless, and requires frequent exercise.



Psittacosaurus

This parrot-beaked herbivore would make a good pet. It lives in herds in the wild, so it's highly sociable and has a fairly gentle temperament.

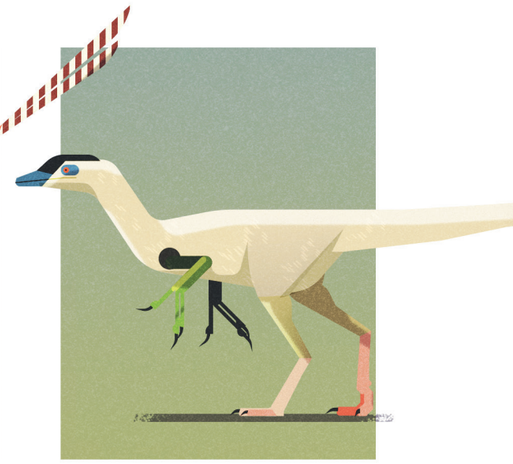
SIZE: Up to 2m in length and 20kg in weight – about the same as a medium-sized dog.
PROS: Has fluffy tail bristles and cute facial horns; helps to keep the lawn tidy by mowing grass with beak.
CONS: Has an unfortunate tendency to gnaw the furnishings.



Yi qi

This teeny, pigeon-sized tree-dweller is the only dinosaur known to have adopted a bat method of flight. Has wings formed of skin membranes, but also tight, downy plumage and four pretty, ribbon-like tail feathers.

SIZE: Positively minute for a dinosaur at 80cm in length and just 380g in weight.
PROS: Small, with short, dense feathers so it doesn't shed much around the house.
CONS: Prone to screechiness; needs large aviary to glide back and forth within.



Compsognathus

The smallest known dinosaur until the 1990s when a variety of dainty, feathered relatives began to turn up in China. Lightly built, so great for small apartments.

SIZE: Turkey-sized but much lighter. It's up to 1m in length but just 3kg in weight.
PROS: Smaller size makes it an ideal lap-dinosaur; it lives in packs so is highly social.
CONS: Needs constant supply of small, live lizards to snack upon; bit of a finger nibbler.

Smaller dinosaurs that infringed on crops or livestock would probably be hunted as 'nuisance' animals, as wolves and dingoes are today, adds Arbour. "It would be really hard for large sauropods to survive alongside us. They're so big and would require so much food, that I doubt we could set aside enough wild spaces for them to thrive."

CITY DWELLERS

The dinosaurs that might do particularly well in the modern era are those that could learn to live and thrive alongside people. In our world today, the vast majority of animal biomass is made up of the species that we farm or have domesticated, or those that live around our cities and developments – and so it would also have been in a reality where humans and dinosaurs co-existed. There might have been dinosaur equivalents of seagulls, pigeons, rats, raccoons and foxes – all very well adapted to take advantage of the resources available in urban environments.

"Small, scrappy dinosaurs might have been able to eke out a living on the margins of housing developments," suggests Farke. You can just imagine little beaked herbivorous dinosaurs nibbling at the roses and hydrangeas in your garden.

"Animals that do well in urban environments today tend to be those that are good at eating whatever we're throwing away, and making use of the structures we build," agrees Arbour. "Small omnivorous or predatory theropods would perhaps have been lurking around garbage cans."

Obviously, we might have domesticated dinosaurs to exploit for meat and eggs or agricultural labour, and we would very likely have taken them into our homes as pets – the feathery or scaly equivalents of dogs and cats.

Perhaps, though, the idea that humans could have evolved in a world filled with dinosaurs is simply too far-fetched. "I have no doubt that we would not be here," says Brusatte. "The asteroid was one of those dominoes that set in motion a chain of events that led to us. Without the dinosaurs disappearing, mammals would not have had the same opportunity."

He argues that mammals had already existed with dinosaurs for 160 million years or more when the asteroid struck. But they were mostly "marginal, shadowy little creatures" and – had the asteroid not caused a mass extinction – would likely remain that way today.

As Brusatte points out: "What's another 66 million years when it had already been like that for 160 million years already."

If all the dinosaurs had survived, their descendants could have given Mr Seagull some competition for your chips

PHOTO: GETTY

"Without the dinosaurs disappearing, mammals would not have had the same opportunity"

John Pickrell is a science journalist, and author of *Flying Dinosaurs*. He tweets from @john_pickrell