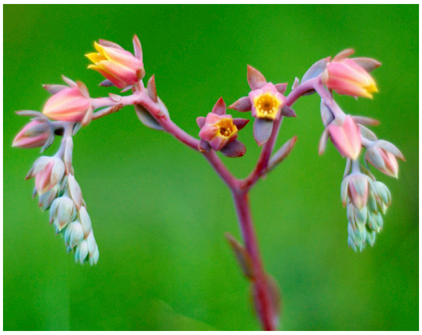

Puzzling plant: Flickr often offers help to those who submit photos of unidentified plants, which others can then help to identify. (Photo: Nathan/Flickr (CC BY 2.0).)

underwater photography are a case in point — photos of manta rays taken by divers mainly for the fun of it are being collected by the Manta Trust and now build up a huge database of individual animals identifiable by their spots (Curr. Biol. (2021) *31*, R973–R976).

Citizen science has by now become a subject of scientific scrutiny itself as the review of Adler and colleagues demonstrates. Accuracy of scientific outcomes and the educational value for participants have been evaluated in detail. As Adler and colleagues admonish, the value for communities and impact on policy have been less appreciated.

When modern science was born, it was an important achievement to take the human out of the equation to obtain objective measures of reality. Today, we have so many machines providing objective measurements that we are more concerned about putting the human back into our scientific enterprise. As Adler and colleagues point out, citizen science is an important way of achieving that.

Mutual benefits for science and participants will ensure that citizen science continues to thrive as a way for both sides to engage with and educate each other. Online technology continues to provide new tools and forums for this cooperation. While AI can take over some of the pattern spotting and species identification work, there will always be enough diving and tree planting to do to keep nature-loving volunteers busy.

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My word

A thing with feathers

Michael J. Benton[1,*], Philip J. Currie[2], and Xing Xu[3]

It was 25 years ago this October that one of the most shocking discoveries in palaeontology was announced: a dinosaur with feathers! Everyone knows that birds have feathers, and indeed feathers are the defining characteristic of birds, so how could some other kind of animal have feathers? Back then, palaeontologists were split in their opinions — if it has feathers it must be a bird, or if it's a dinosaur then the 'feathers' must be something else. Initial squabbles about the fossil's provenance and the fact that the type specimen of this first feathered dinosaur — *Sinosauropteryx prima* — was apparently split in two with each half in a different museum added to the intrigue. But in the 25 years that followed, thousands of feathered dinosaur fossils from China and elsewhere have revolutionized our understanding of the origin of birds, of flight, of dinosaurian behaviour, and of the origins of endothermy in vertebrates.

Naming *Sinosauropteryx*

The first feathered dinosaur was named *Sinosauropteryx*, meaning 'Chinese reptile wing,' a name deliberately evoking the classic *Archaeopteryx* ('ancient wing'). It was described in a Chinese-language article published in September 1996 by Qiang Ji and Shu-an Ji[1] based on the half of the specimen in the National Geological Museum of China (CGM). Ji and Ji referred to the feathers over the back of the head, neck, torso and in tufts along the tail. Two years later, the first English-language publication appeared in *Nature*[2], cautiously calling the feathers 'protofeathers.' This paper presented the counterpart of the previously described fossil, housed in the Nanjing Institute of Geology and Palaeontology (NIGPAS; Figure 1). The fossils show a one-metre-long bipedal animal, pirouetting on one foot, with the head tipped back, short arms tucked in and upward tail behind. The specimen also shows black melanin pigment in the eye as well as possible organic remains within the rib cage. The researchers knew this was an epochal discovery, and they were right, but how did such an important specimen get split in two?

We have reconstructed the events of 1996. One of us (Phil Currie) was in Mongolia excavating dinosaurs and flew to Beijing on September 18 to see Zhiming Dong at the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP). Press reports appeared at this point in Beijing, showing the CGM specimen, and on September 23 Currie and Dong met Qiang Ji, who showed them photographs. Dong was keen on Currie helping to prepare an English-language version of the paper, but the photographs were too poor to determine what the 'feathers' were.

Two days later, Dong and Currie went to the Geological Museum downtown. Currie was surprised that, instead of being shown the specimen, he was ushered into a conference room packed with the Chinese press with cameras and microphones. He sat down at the front of the room with Qiang Ji, and people brought in silk-covered Chinese gift boxes hand made for individual specimens. Ji opened each box one at a time and showed Currie the specimens, first a beautiful *Psittacosaurus*, then insects, fish, lizards, a mammal with fur, birds, etc. By then, Currie was convinced that they were not going to show him the feathered dinosaur. Ji then opened without announcement another box and Currie's jaw dropped as he saw the specimen (Figure 1A) for the first time.

All his doubts were removed in an instant. This was a small dinosaur, similar to the little theropod *Compsognathus* long known from Germany. He was flabbergasted as he examined the specimen with only a magnifying glass. The press left after about an hour. Currie had been asked many questions that were translated by Dong. Ji had indicated that he wanted to work with him on the theropod, but some time during the interview Currie could feel that something changed. After a tour of the museum, Dong gave Currie news that Qiang Ji's bosses had told him suddenly that a German team was going to study the specimen and he would not be involved. The most likely explanation for this change of mind is that Currie saw this was a dinosaur, while Ji identified it as a bird — because it had feathers — and indeed it was named as a bird in that first paper[1].

Currie flew back to Canada at the end of September 1996, wondering what would happen with the amazing new specimen, and what had happened to the counterpart slab. At the same time, word was getting out. There had been a Japanese reporter at the Beijing press conference, and the UK press also got word and contacted Currie for comments. Currie met Peiji Chen at the Society for Vertebrate Paleontology (SVP) congress in New York on October 16, where he saw photographs of the Nanjing specimen (Figure 1) for the first time, and was invited to collaborate in describing it. On October 17, Currie was interviewed by *Earth*, *Science* and *Science News* magazines and the following day by Malcom Browne from the *New York Times* where an article appeared on the front page.

The *New York Times* article caused a sensation worldwide, but especially at the SVP meeting still underway in New York. Chen did not give a talk, but he was everywhere pursued by journalists, and in close discussions with Currie, as well as other senior palaeontologists including Farish Jenkins (Harvard) and John Ostrom (Yale).

By November, the description of the CGM specimen had been published[1], and it was informally translated into English. At NIGPAS, Currie worked on the counterpart specimen and another that had been purchased earlier. In this third slab, many of the 'feathers' had been prepared off by the farmer who found it. In fact, many of the astonishing fossils from China have been first found by farmers who may have limited knowledge of palaeontology, but with practical skills and a desire to make their discoveries look beautiful, ready for sale. Chen had shown photos of this specimen

Figure 1. A feathered fossil.
The theropod dinosaur *Sinosauropteryx* from the Early Cretaceous of China, showing the counterpart of the original specimen and interpretative drawing (NIGPAS 127586; images: Fiann Smithwick).

at a conference in the United States in summer 1996, when various researchers had seen it. Chen and Currie continued their studies of both NIGPAS specimens for six days, but then Currie was told by the NIGPAS director that he would not be a coauthor on the first publication[2], but he was a co-author of a subsequent paper that presented more detailed descriptions[3].

Back in 1996, palaeontology in China was a very small discipline, with few researchers who had limited contact with scientists in other countries. The country was emerging from a long period of isolation and the economy was beginning to improve. The visits by Phil Currie at the time were unusual and mark the beginning of a boom in palaeontological research in China, where the new fossils propelled investment and a massive growth in the international impact of Chinese research.

Origin of birds and of flight

After *Sinosauropteryx*, thousands of similar fossils were found in the Middle–Late Jurassic deposits of China, such as the Tiaojishan Formation, and Early Cretaceous deposits, such as the Yixian Formation, and others. By 2008, these fossils corresponded to 29 species of dinosaur and 27 species of bird[4]. Today, there are some 55 species each of dinosaurs and birds, of which over 30 dinosaurs have feathers.

Figure 2. *Sinosauropteryx* at 25.
Life reconstruction of *Sinosauropteryx* by Jim Robins.

The impact on our understanding of dinosaurs and bird evolution has been profound. By 1996, most palaeontologists accepted John Ostrom's evidence[5] that birds were dinosaurs, in fact resurrecting the smart comment by Thomas Huxley 100 years earlier that *Archaeopteryx*, the first bird, was 'a dinosaur in bird's clothing'. Some continued to oppose this view[6], preferring to see birds originating from an unknown ancestor in the Triassic, but the results of numerous cladistic analyses confirmed Huxley's and Ostrom's insight[7–11] based on hundreds of anatomical traits shared by birds with dinosaurs in general and paravian dinosaurs in particular.

In terms of phylogeny, in the past 25 years the Chinese feathered dinosaur and bird fossils contributed to a shift of nearly all those unique bird characters back down the evolutionary tree as they were identified in one dinosaur or another. In the time of Thomas Henry Huxley — who first saw the link between birds and reptiles — knowledge of the fossil record of birds was minimal, and the only known fossil bird-like animal was *Archaeopteryx*. Modern birds and *Archaeopteryx* were thought to share thirty or more unique features not seen in dinosaurs, such as hollow bones, fused clavicles (furcula, wishbone), large hands and forearms, the semilunate carpal (enabling them to fold their wings back), feathers, pennate feathers (with central rachis and branching barbs) and presumed powered flight. All of these features have now been relegated to more basal nodes in the dinosaur and bird phylogeny, some to the roots of theropods, others to intermediate steps through dinosaurian evolution[9]. Even powered flight is no longer unique to birds, as there is evidence that the dromaeosaurid dinosaurs *Microraptor* and *Rahonavis* were probably able to flap their wings[12].

That powered flight could have evolved independently was not expected, and that some of the early flyers, such as *Microraptor*, flew on four wings was also unexpected. Scansoriopterygids, such as *Yi*, even had membranous, bat-like wings, further confirming the extent of evolutionary 'experimentation' during the origin of theropod flight[13]. Further, the sheer diversity of tiny feathered theropods found in China was surprising. While most theropods were evolving to become larger to overpower ever-larger herbivore prey, the paravians shrank in the Middle Jurassic, likely in pursuit of insects in the trees and modified their feathers for camouflage and flight. Furthermore — and unexpectedly — it turned out that gliding with stiff wings and powered flight with flapping wings were not independent adaptations, but that gliding had evolved seamlessly into sustained flying[12,13].

Dinosaurian colour and behaviour

Who would have predicted in 1996 that the colour of dinosaurian feathers could be determined? In 2010, two teams[14,15] showed that feathers of *Sinosauropteryx* and *Anchiornis* bore diverse melanin-based colours in striking patterns of bars, stripes and spangles (Figure 2). These were evidence for display-type coloration and that these small dinosaurs at least were likely to have engaged in display behaviour, as in many birds. Further, colours showed evidence of countershading, a camouflage pattern that breaks up the outline of prey species[16,17].

These discoveries have served as exemplars of the replacement of speculation by science, where palaeobiologists present chains of inference for previously speculative topics, such as colour. Instead of fruitless squabbling over opinions, palaeobiologists now are able to debate the evidence for colour, diet, locomotion, reproduction and other themes based on direct evidence in the fossils[18,19].

Origins of endothermy in vertebrates

A further unexpected outcome of the new feathered dinosaurs has been the wider occurrence of feathers, and their meaning. Feathers are found in theropod and ornithischian dinosaurs, and are therefore likely to have arisen with the origin of dinosaurs[9]. In fact, the suggestion that pterosaur pycnofibres might also be feathers[20] extends the origin of feathers even deeper into archosaur phylogeny. Either way, feathers are likely to have originated in the Early Triassic, some 100 million years before *Archaeopteryx*. Therefore, they did not function in flight initially, but were likely part of a suite of adaptations to endothermy.

This coincides with evidence from bone histology, inferred lung structures and hearts that the Early Triassic dinosaurs and close relatives were warm-blooded from the start, evolving this innovation in parallel with the synapsids, ancestors of mammals, that have long been suspected of endothermy[21]. The Early Triassic was a time of major upheaval of life, following the end-Permian mass extinction 252 million years ago when over 90% of species died out. This recovery time saw modern-style ecosystems emerge, and a possible arms race between synapsids and dinosaurs, improving their endothermy, respiration and gait at the same time to maintain high activity levels and run for longer than their cold-blooded counterparts.

Chinese palaeontology to the fore

In many ways, the confused discussions about an unusual new bird-dinosaur in 1996 have had profound consequences for our understanding of the history of life in the past 25 years! But not only that. In those 25 years, Chinese palaeontology has risen from quite a low level of international exposure to now being one of the leading nations publishing high-impact work in the field. Over the same time span, remarkable new fossil localities have stimulated rapidly maturing research in numerous institutions in China, and thousands of publications each year in the leading journals. The two institutions that were the focus of palaeontological research in the 1990s (NIGPAS, IVPP) have grown substantially, active palaeontological research has been established in 100 or more universities and other museums, and in fact palaeontology is rated by the Chinese Academy of Sciences as one of the leading research fields in which China has achieved high international recognition[22].

The little dinosaur *Sinosauropteryx*, first described a quarter century ago, has been a focus of interest throughout this revolution: first as witness to the debate about whether feathers originated before the origin of birds or not, then the remarkable discovery that palaeontologists could reconstruct colours and patterns of the plumage of long-extinct animals, and now over broader questions about the origins of flight and endothermy. Such spectacular fossils not only give us a sense of wonder at their beauty and remarkable freshness after so many millions of years, but they are key to unlocking so many important advances in understanding of key events and processes in the deep-time evolution of life.

REFERENCES

1. Ji, Q., and Ji, S. (1996). On the discovery of the earliest bird fossil in China (*Sinosauropteryx* gen. nov.) and the origin of birds. Chinese Geol. *10*, 30–33.
2. Chen, P., Dong, Z., and Zhen, S. (1998). An exceptionally well-preserved theropod dinosaur from the Yixian Formation of China. Nature *391*, 147–152.
3. Currie, P.J., and Chen, P.J. (2001). Anatomy of *Sinosauropteryx prima* from Liaoning, northeastern China. Can. J. Earth Sci. *38*, 705–727.
4. Benton, M.J., Zhou, Z.H., Orr, P.J., Zhang, F.C., and Kearns, S.J. (2008). The remarkable fossils from the Early Cretaceous Jehol Biota of China and how they have changed our knowledge of Mesozoic life. Proc. Geol. Ass. *119*, 209–228.
5. Ostrom, J.H. (1976). *Archaeopteryx* and the origin of birds. Biol. J. Linn. Soc. *8*, 91–182.
6. Feduccia, A. (2002). Birds are dinosaurs: simple answers to a complex problem. Auk *119*, 1187–1201.
7. Gauthier, J. (1986). Saurischian monophyly and the origin of birds. Mem. Calif. Acad. Sci. *8*, 1–55.
8. Norell, M.A., Clark, J.M., and Makovicky, P.J. (2001). Phylogenetic relationships among coelurosaurian theropods. In New Perspectives on the Origin and Early Evolution of Birds, J. Gauthier and L.F. Gall, eds. (New Haven: Yale University), pp. 49–67.
9. Xu, X., Zhou, Z., Dudley, R., Mackem, S., Chuong, C.-M., Erickson, G.M., and Varricchio, D.J. (2014). An integrative approach to understanding bird origins. Science *346*, 1253293.
10. Brusatte, S.L., O'Connor, J.K., and Jarvis, E.D. (2015). The origin and diversification of birds. Curr. Biol. *25*, R888–R898.
11. Cau, A. (2018). The assembly of the avian body plan: a 160-million-year long process. Boll. Soc. Paleontol. Ital. *57*, 1–25.
12. Pei, R., Pittman, M., Goloboff, P.A., Dececchi, T.A., Habib, M.B., Kaye, T.G., Larsson, H.C.E., Norell, M., Brusatte, S.L., and Xu, X. (2020). Potential for powered flight neared by most close avialan relatives, but few crossed its thresholds. Curr. Biol. *30*, 4033–4046.
13. Xu, X., Zheng, X., Sullivan, C., Wang, X., Xing, L., Wang, Y., Zhang, X., Connor, J.K.O., Zhang, F., and Pan, Y. (2015). A bizarre Jurassic maniraptoran theropod with preserved evidence of membranous wings. Nature *521*, 70–73.
14. Li, Q., Gao, K.Q., Vinther, J., Shawkey, M.D., Clarke, J.A., D'Alba, L., Meng, Q., Briggs, D.E.G., and Prum, R.O. (2010). Plumage colour patterns of an extinct dinosaur. Science *326*, 1369–1372.
15. Zhang, F.C., Kearns, S.L., Orr, P.J., Benton, M.J., Zhou, Z.H., Johnson, D., Xu, X., and Wang, X.L. (2010). Fossilized melanosomes and the colour of Cretaceous dinosaurs and birds. Nature *463*, 1075–1078.
16. Vinther, J., Nicholls, R., Lautenschlager, S., Pittman, M., Kaye, T.G., Rayfield, E., Mayr, G., and Cuthill, I.C. (2016). 3D camouflage in an ornithischian dinosaur. Curr. Biol. *26*, 2456–2462.
17. Smithwick, F.M., Nicholls, R., Cuthill, I.C., and Vinther, J. (2017). Countershading and stripes in the theropod dinosaur *Sinosauropteryx* reveal heterogeneous habitats in the Early Cretaceous Jehol biota. Curr. Biol. *27*, 3337–3343.
18. Benton, M.J. (2019). Dinosaurs Rediscovered: The Scientific Revolution in Paleontology (London and New York: Thames & Hudson).
19. Benton, M.J. (2019). The Dinosaurs: New Visions of a Lost World (London and New York: Thames & Hudson).
20. Yang, Z., Jiang, B., McNamara, M.E., Kearns, S.L., Pittman, M., Kaye, T.G., Orr, P.J., Xu, X., and Benton, M. (2019). Pterosaur integumentary structures with complex feather-like branching. Nat. Ecol. Evol. *3*, 24–30.
21. Benton, M.J. (2021). The origin of endothermy in synapsids and arms races in the Triassic. Gondwana Res. In press, https://doi.org/10.1016/j.gr.2020.08.003.
22. Jia, H.P. (2019). Paleontology: advancing China's international leadership. Natl. Sci. Rev. *6*, 171–176.

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