yet fully integrate the devastation caused by the asteroid strike with that caused by the longer-running Deccan Trap eruptions in India".

Although generally I enjoyed the book, I cannot agree that paleontology has become a true science only in the past 40 years. This period marks the discovery of many exceptionally preserved new dinosaur species that constitute the basis for changing our understanding of dinosaur biology. Discovery of a fact or truth about nature is itself part of the science and often constitutes the most fascinating aspect to the public. No one would doubt the significance of discovering the Higgs boson in physics. Paleontologists should not be bothered by being called 'stamp collectors', a term that is itself unfairly used for many scientific disciplines that are often dealing with complex natural phenomenon and rely on endless observations and the collection of important samples. The current trend in the study of paleontology is almost certainly characterized by an integration of biological and geological progress and the application of new technologies that produce revolutionary ideas about dinosaur biology, yet nothing would be as exciting to both paleontologists and the public alike as the revolutionary discoveries themselves.

REFERENCES

1. Wang, M., O'Connor, J.K., Xu, X., and Zhou, Z. (2019). A new Jurassic scansoriopterygid and the loss of membranous wings in theropod dinosaurs. Nature *569*, 256–259.
2. Nyakatura, J.A., Melo, K., Horvat, T., Karakasiliotis, K., Allen, V.R., Andikfar, A., Andrada, E., Arnold, P., Lauströer, J., Hutchinson, J.R., *et al.* (2019). Reverse-engineering the locomotion of a stem amniote. Nature *565*, 351–355.
3. O'Connor, J.K. (2019). The trophic habits of early birds. Palaeogeogr. Palaeocl. *513*, 178–195.
4. Pan, Y., Zheng, W., Sawyer, R.H., Pennington, M.W., Zheng, X., Wang, X., Wang, M., Hu, L., O'Connor, J., Zhao, T., *et al.* (2019). The molecular evolution of feathers with direct evidence from fossils. Proc. Natl. Acad. Sci. USA *116*, 3018–3023.
5. Lindgren, J., Sjövall, P., Thiel, V., Zheng, W., Ito, S., Wakamatsu, K., Hauff, R., Kear, B.P., Engdahl, A., Alwmark, C., *et al.* (2018). Soft-tissue evidence for homeothermy and crypsis in a Jurassic ichthyosaur. Nature *564*, 359–365.
6. Schoene, B., Eddy, M.P., Samperton, K.M., Keller, C.B., Keller, G., Adatte, T., and Khadri, S.F.R. (2019). U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction. Science *363*, 862–866.

Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, P.O. Box 643, Beijing 100044, China.
E-mail: zhouzhonghe@ivpp.ac.cn

Quick guide

Cuckoo catfish

Martin Reichard

Why 'cuckoo' catfish? The 'cuckoo' part of the name references the cuckoo bird. Like their bird counterparts, cuckoo catfish smuggle their eggs into the care of foster parents. This reproductive strategy of relinquishing parental duties to foster parents — known as brood parasitism — has evolved on several independent occasions in unrelated animal groups. In a few species, it has developed to the point that parents can no longer raise their own offspring — termed obligatory brood parasitism.

Why are cuckoo catfish special? Among vertebrates, only a few bird lineages have evolved obligatory brood parasitism. Social insect (ants, bees, wasps and also some beetles) are invertebrate examples. Uniquely among brood parasites, the cuckoo catfish (*Synodontis multipunctatus*) has evolved brood parasitism even though its relatives show no parental care. The cuckoo catfish is a member of a small group of squeaker catfishes (family Mochokidae) from Lake Tanganyika, with approximately ten locally endemic species. With the exception of the cuckoo catfish, all other squeaker catfish species (in Lake Tanganyika and elsewhere) reproduce by scattering their eggs during mating and provide no care to their young.

Who is parasitized? The cuckoo catfish exploits the parental care of mouthbrooding cichlids. Haplochromine cichlids have undergone spectacular species radiations in the African Great Lakes (Tanganyika, Malawi and Victoria), and this diversification is thought to have been facilitated by their strong parental habits. These cichlids lay their eggs in a specially prepared nest, and female mouthbrooders collect their eggs immediately after spawning to incubate them in their mouths for a period of about three weeks.

How do cuckoo catfish fool cichlids? Cuckoo catfish invade cichlid nests during spawning where they quickly deposit their own eggs which then are mistakenly collected by the female cichlid. Observations in captivity show that groups of cuckoo catfish can overwhelm spawning pairs of cichlids, disrupting spawning and attempting to eat the cichlid's eggs. Male cichlids respond aggressively to intruding catfish, but repeated intrusions by groups of cuckoo catfish eventually enable them to spawn with the cichlids. The catfish release batches of about 10 eggs at a time. When catfish eggs are released, female cichlids may inadvertently collect some of them in their mouths as they quickly try to pick up their own eggs, which are at risk of being eaten by intruding catfish.

Why don't cichlids avoid catfish eggs? Catfish chicanery does not include egg visual mimicry. Catfish eggs are markedly different in shape and are smaller than the eggs of their hosts (Figure 1). Recent experiments suggest that cichlid hosts that coexist with cuckoo catfish in Lake Tanganyika may be able to selectively reject cuckoo catfish eggs, but how host females discriminate cuckoo catfish eggs is still unknown. Strikingly, mouthbrooders from other African lakes seem helpless once infected with catfish eggs. So far, too few host species have been studied to see whether this is a general pattern, but it seems that — as in cuckoos and their host birds— a coevolutionary 'arms race' operates between cuckoo catfish and Lake Tanganyika cichlids, while catfish are one evolutionary step ahead of cichlids from all other locations.

What is the fate of the host brood? Having a cuckoo catfish as a step-sibling is fatal for baby cichlids. Catfish eggs hatch earlier than those of cichlids. However, unlike avian cuckoo chicks, which often evict host offspring from the nest, baby cuckoo catfish devour the host embryos, one by one, over several days (Figure 1). Cichlid embryos have a large yolk sac, a nutrient-rich energy supply to sustain their long incubation in

the parent's mouth, and this serves as food for the parasitic catfish. By the end of oral incubation all host embryos have usually been consumed and cuckoo catfish may resort to cannibalism.

Cuckoo catfish embryos are well equipped for consuming the offspring of their host. They develop quicker than cichlids and their wide mouth is armed with formidable embryonic teeth, evidently an adaptation to their unusual biology. After weeks devoted to their care and protection, the female cichlid releases the young catfish from her mouth instead of her own offspring. Ironically, catfish eggs not collected by a cichlid when spawned (and perhaps even those that were rejected) might get a second chance to infect a mouthbrooding cichlid later on. Catfish eggs can hatch and develop outside the cichlid's mouth. As the maternal instincts of female cichlids are strong, mouthbrooding females often indiscriminately collect stray heterospecific offspring they encounter, which, at least in captivity, can include cuckoo catfish.

Are all mouthbrooding cichlids exploited? In Lake Tanganyika where the cuckoo catfish is endemic, only six cichlid species have been confirmed as cuckoo catfish hosts, with 1.4–15% of brooding females infected in these species. Notably, this estimate is based on a single study at one location. As cuckoo catfish are distributed throughout Lake Tanganyika (which is 673 km long), it remains to be seen how prevalent cuckoo catfish parasitism is in other parts of the lake.

In captivity, mouthbrooding cichlids from other African lakes are commonly infected at a much higher rate than Tanganyikan cichlids. On average, one third of clutches were infected in non-Tanganyikan cichlids, but with great variation among host species. Natural cuckoo catfish hosts, in contrast, are parasitized much less frequently, typically at a rate of 6–15% of broods. This rate is comparable to that in Lake Tanganyika, suggesting that cichlids coexisting with cuckoo catfish have evolved mechanisms to mitigate the success of catfish parasites.

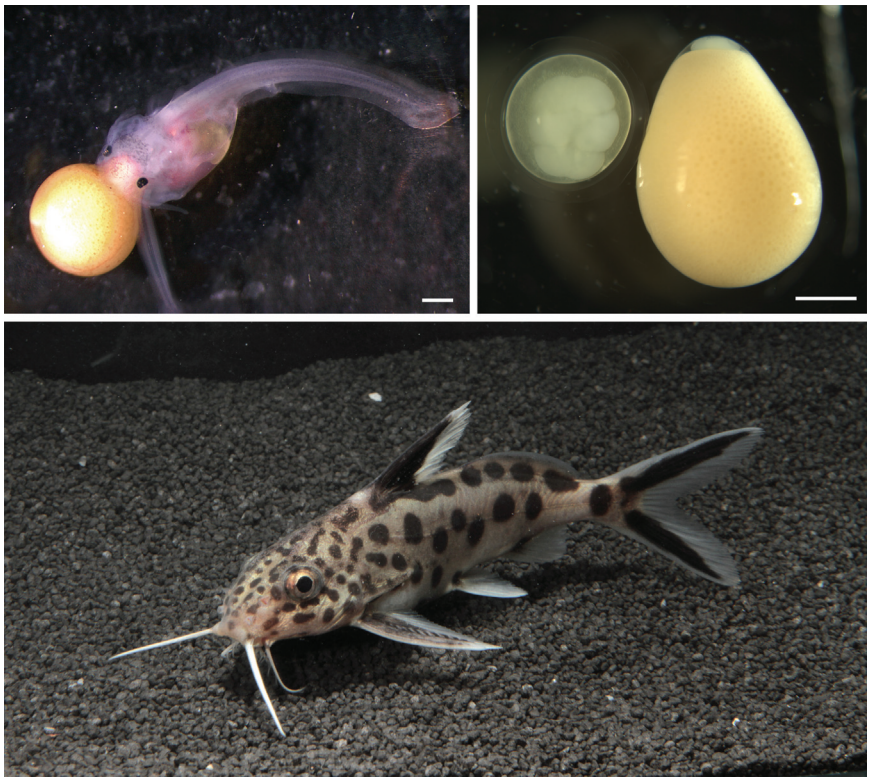

Figure 1. The cuckoo catfish and embryos of its hosts.
Top left: cuckoo catfish embryos feed on embryos of their host, latching on to the head of a hatched cichlid and gradually swallowing the entire embryo (top left; 6 days post fertilization). Top right: the eggs of the cuckoo catfish are round and considerably smaller than the oval, nutrient-rich eggs of their hosts. Bottom: an adult cuckoo catfish. Photo credits: M. Brent Hawkins (top) and Radim Blažek (bottom).

But how could this all have started in the first place? Unlike in birds and insects, cuckoo catfish parasitism could not have initially evolved through brood parasites exploiting hosts within their own species, because this group of catfish lacks parental care. Instead, these catfish appear to opportunistically join cichlid spawning pairs as egg predators, providing a possible route to parasitism through the spatial and temporal overlap of spawning. Alternatively, the strong maternal instinct of cichlids to collect stray offspring may have led to the exploitation of mouthbrooding cichlids by catfish.

Our understanding of cuckoo catfish brood parasitism, and its evolutionary origins, is still rudimentary but the species promises to bring fresh new insight into our understanding of how brood parasitism can evolve and persist. More than 30 years after the first discovery of the cuckoo catfish reproductive strategy in Lake Tanganyika, the time has now come to tease apart the details of this remarkable association using a combination of field and lab experiments.

Where can I find out more?

Blažek, R., Polačik, M., Smith, C., Honza, M., Meyer, A., and Reichard, M. (2018). Success of cuckoo catfish brood parasitism reflects coevolutionary history and individual experience of their cichlid hosts. Sci. Adv. *4*, eaar4380.

Cohen, M.S., Hawkins, M.B., Knox-Hayes, J., Vinton, A.C., and Cruz, A. (2018). A laboratory study of host use by the cuckoo catfish *Synodontis multipunctatus*. Environ. Biol. Fish. *101*, 1417.

Cohen, M.S., Hawkins, M.B., Stock, D.W., and Cruz, A., (2019). Early life-history features associated with brood parasitism in the cuckoo catfish, *Synodontis multipunctatus* (Siluriformes: Mochokidae). Phil. Trans. R. Soc. *B 374*, 20180205.

Polačik, M., Reichard, M., Smith, C., and Blažek, R. (2019). Parasitic cuckoo catfish exploit parental responses to stray offspring. Phil. Trans. R. Soc. B *374*, 20180412.

Sato, T. (1986). A brood parasitic catfish of mouthbrooding cichlid fishes in Lake Tanganyika. Nature *323*, 58–59.

Institute of Vertebrate Biology, Academy of Sciences of the Czech Republic, Květná 8, Brno, Czech Republic.
Email: reichard@ivb.cz