Inside the oldest bird brain

Lawrence M. Witmer

Did *Archaeopteryx*, the most primitive known bird, have ‘the right stuff’? Looking into its skull with advanced technology provides insight into the dinosaurian transition to birds, and the evolution of flight.

Archaeopteryx may not be a global star of the calibre of, say, *Tyrannosaurus rex*, but it undoubtedly has iconic status. Combining the feathered wings and wishbone of birds with the toothed jaws and long bony tail of reptiles (Fig. 1), *Archaeopteryx* is the near-perfect transitional form. Since its discovery shortly after the publication of Charles Darwin’s *Origin of Species* in 1859, it has been a compelling example in the case for evolution.

It has also been the central player in the debate on the origin of birds and avian flight. Although discoveries of feathered dinosaurs and archaic birds from China have advanced our understanding of the transition to birds[1,2], the *Archaeopteryx* skeletons collected from Jurassic limestones in southern Germany remain (at 147 million years old) the oldest undisputed avian fossils, and the most primitive[3]. The fossils have been scrutinized by so many scientists over the past 140 years that it might seem that nothing new could be learned. But a landmark study by Domínguez Alonso *et al.*, on page 666 of this issue[4], goes back to the first skeleton ever found to present exciting data on the brain and sense organs. The results have implications for both the biology of *Archaeopteryx* and the evolutionary transition to birds.

Researchers at the Natural History Museum in London isolated the part of the skull that in life encased the brain (Fig. 2). The braincase is so tiny — smaller than the last segment of your little finger — that Angela Milner, the team leader, safely carried it in a box in her shirt pocket from London to the University of Texas at Austin, where it could be analysed with high-resolution X-ray computed tomography. Using X-rays, the team ‘sliced’ the braincase so finely (each slice less than half the thickness of a printed page of *Nature*) that they were able to peer inside the thin bone at the brain cavity and inner ear (the organ of balance and hearing), which was then digitally reconstructed.

Figure 1 **Iconic *Archaeopteryx*. This is the ‘Berlin specimen’, discovered in 1877 and now kept at the Humboldt Museum in Berlin. The ‘London specimen’, which Domínguez Alonso *et al.*[4] worked with, was discovered earlier (in 1861) and, although the head was separated from the body, it preserves the part of the skull enclosing the brain in exquisite detail.**

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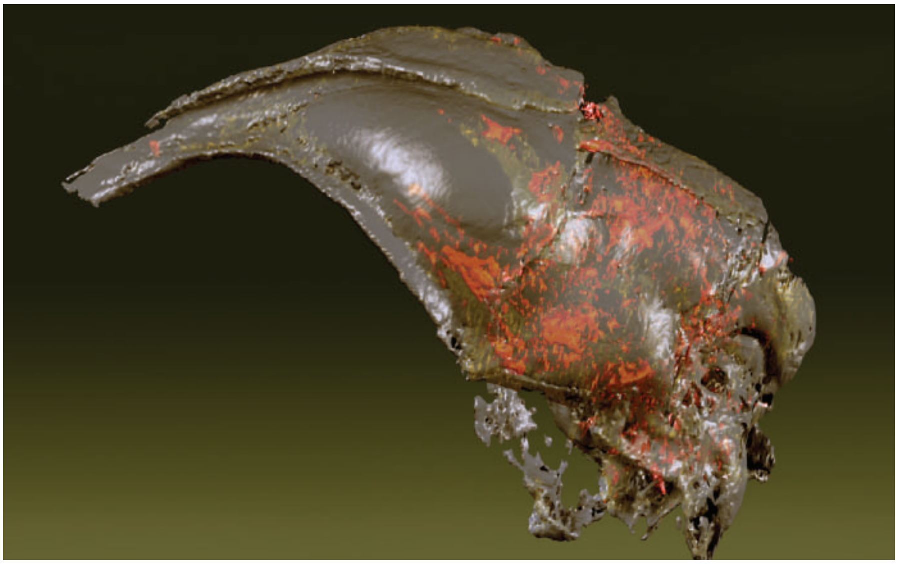

Figure 2 **Bird brain? The three-dimensional reconstruction of the braincase and brain of *Archaeopteryx*, produced by Domínguez Alonso and colleagues using computed tomography. From their analyses of the brain and inner ear, they conclude that *Archaeopteryx* was probably equipped for flight. The reconstruction is about 20 mm in length; the red areas are crystals of manganese dioxide deposited during fossilization.**

P. DOMÍNGUEZ ALONSO

Obtaining an understanding of the brain and sense organs is a top priority for palaeontologists, because such knowledge can offer insight into the behaviour of extinct organisms not otherwise provided by the skeleton. In the case of *Archaeopteryx*, from the beginning the question has been — could the oldest-known bird fly? In the past, answers have been sought from aerodynamics, justifiably focusing on the structure of the wings and feathers[3,5]. But flight isn’t just about wings, rudders and flaps. It’s also about the pilot and on-board computer, and those are the missing elements that this new study[4] provides for *Archaeopteryx*.

The brain of *Archaeopteryx* was much like that of birds today, albeit of a primitive sort. It was larger than the brain of an average reptile of equivalent body size but smaller than any similarly sized modern bird brain. Its organization was also basically avian, with enhancement of those areas concerned with movement. Moreover, the visual centres are enlarged, suggesting that *Archaeopteryx* was a visually oriented animal. The new findings relating to the delicate inner-ear canals are particularly important, because recent studies have associated canal architecture with behaviour and mode of life[6,7]. The canals of *Archaeopteryx* are again much more like those of birds than modern-day reptiles, suggesting that agility and coordination of head and eye movements were critical.

But is this the brain and ear of a flier? Some insight here can be provided by the entirely separate evolution of flight in pterosaurs, the extinct flying-reptile group that dominated the skies between 230 million and 65 million years ago. A computed tomography study of pterosaurs[6] that my colleagues and I carried out revealed expansion and reorganization of the brain and inner-ear canals very much like that seen in *Archaeopteryx*; and brain size relative to body size is almost identical. These independently evolved similarities suggest that there may indeed be some fundamental neural requirements for flight. In fact, Domínguez Alonso *et al.*[4] argue that *Archaeopteryx* basically had 'the right stuff', from a neural standpoint, for flight. The authors also note, however, that some of the predatory (theropod) dinosaurs — the group that includes *Archaeopteryx* and all other birds — show some brain traits similar to those seen in birds. Domínguez Alonso *et al.* suggest that *Archaeopteryx* exhibits "a stage further towards the modern bird pattern". That hypothesis probably represents the most exciting outcome of this study: we finally have reliable data on the brain and inner ear of the most primitive known bird, and so can document the neural transition to birds.

Researchers will now race to the fossils of other early birds and bird-like theropods to look for the features identified in *Archaeopteryx*. What are the details of the transition? Did all of the 'avian' neural components evolve together or was this a piecemeal process? It might turn out that the non-flying progenitors of birds had developed many of these components. If so, then whereas pterosaurs clearly built their neural flight-control system from scratch[6], birds may have evolutionarily co-opted for flight the advanced neural machinery they inherited, which was subsequently honed as flight improved. Perhaps most controversially, if a 'flight brain' or 'flight ear' can ever be characterized, can it provide a test of the heretical notion that some of the most bird-like Cretaceous theropods (such as *Velociraptor*) are actually the secondarily flightless descendants of early, *Archaeopteryx*-like birds[8]?

This latest in a long line of papers on *Archaeopteryx* affirms the iconic status of this fossil. It shows yet again that, in large measure, it all begins and ends with *Archaeopteryx*. ■

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1. Xu, X. *et al. Nature* **421,** 335–340 (2003).
2. Zhou, Z., Barrett, P. M. & Hilton, J. *Nature* **421,** 807–814 (2003).
3. Elzanowski, A. in *Mesozoic Birds* (eds Chiappe, L. M. & Witmer, L. M.) 129–159 (Univ. California Press, Berkeley, 2002).
4. Domínguez Alonso, P., Milner, A. C., Ketcham, R. A., Cookson, M. J. & Rowe, T. B. *Nature* **430,** 666–669 (2004).
5. Rayner, J. M. V. in *Biomechanics in Evolution* (eds Rayner, J. M. V. & Wootton, R. J.) 183–212 (Cambridge Univ. Press, 1991).
6. Witmer, L. M., Chatterjee, S., Franzosa, J. & Rowe, T. *Nature* **425,** 950–953 (2003).
7. Spoor, F. *et al. Nature* **417,** 163–166 (2002).
8. Paul, G. S. *Dinosaurs of the Air: The Evolution and Loss of Flight in Dinosaurs and Birds* (Johns Hopkins Univ. Press, Baltimore, 2002).

Semiconductor physics

The value of seeing nothing

Jochen Mannhart and Darrell G. Schlom

Adding atoms to a semiconductor can improve its electronic properties. In an oxide, taking atoms away can have a similar electronic effect — one that could, it seems, be exploited in device applications.

By 2007, the information age will have hit a fundamental roadblock. Without major changes in technology, the spectacular improvements in computer performance that we have enjoyed for decades will cease, because transistors based on silicon and silicon dioxide will no longer be able to keep up with Gordon Moore's famous law[1,2] — that the number of transistors per unit area in an integrated circuit doubles every couple of years. But these limitations might be overcome if Si and SiO_2 were complemented in these devices by other materials. The candidates of choice are oxides, which are already assuming a vital role in semiconductor electronics. Now Muller *et al.*[3] (page 657 of this issue) show that it is possible to control the electronic properties of these materials with the nanoscale precision necessary for the information industry.

Oxides offer a broad spectrum of properties — some are excellent insulators, others are superconductors. Some oxides have flippable electric or magnetic dipoles, suggesting myriad device possibilities. Indeed, oxides such as hafnium dioxide are forecast to replace SiO_2 in the transistors of laptop computers within only three years[1]. Another oxide known as 'Lustigem' — alias strontium titanate ($SrTiO_3$) — was a popular diamond substitute in the 1960s. If some of its oxygen atoms are removed, the glittering gem turns a deep blue (Fig. 1), and changes from insulating to conducting. This change in colour and conductivity is due to electrons that are left behind: because there is a difference in charge between an oxygen ion (O^{2-}) and an oxygen atom, for each oxygen atom removed two electrons are added to the $SrTiO_3$ matrix. Oxygen vacancies thus function as electron-donating dopants — an effect commonly achieved in semiconductors by replacing some atoms with others that contain more or fewer electrons than the atoms for which they substitute. But can doping through vacancies be implemented and monitored in a controlled way on the atomic scale?

Figure 1 **Now you see it, now you don't. These micrographs of a $SrTiO_3$ crystal show the effect of removing oxygen atoms, leaving vacancies in the crystal lattice: the glistening oxidized gem (top) is transformed into a dull blue, conductive crystal (bottom).**

It seems so. Muller and colleagues[3] have made an unexpected double breakthrough. With unrivalled precision, they have measured the quantity and location of oxygen vacancies in films consisting of layers of fully oxidized $SrTiO_3$ and of $SrTiO_{3-\delta}$, in which some oxygen atoms are missing. Their first major advance is to have grown alternating layers of doped ($\delta \neq 0$) and undoped ($\delta = 0$) $SrTiO_{3-\delta}$, where a layer may be as thin as three unit cells. Analogous 'superlattices' are used in conventional semiconductor technology to enhance the lifetime of charge carriers[4]; in oxide superconductors, they are used to increase the supercurrent density[5]. Muller *et al.* grew their superlattices using pulsed laser ablation — a popular research technique for depositing thin films of oxide materials. Deposition occurs when a laser beam hits a $SrTiO_3$ target inside a vacuum chamber, vaporizing its surface into a plasma. Some of the vaporized atoms condense on a nearby substrate, again of $SrTiO_3$, heated to 750 °C. Adjusting the oxygen pressure in the chamber controls the δ of the single crystalline $SrTiO_{3-\delta}$ layers deposited.

To image the oxygen vacancies, the authors used a scanning transmission electron microscope (STEM). As the tightly focused electron beam of the STEM is scanned across a cross-sectional slice of the deposited superlattice, a map is made of the positions where electrons are scattered slightly by oxygen vacancies and related