When is a bird not a bird?

Kevin Padian

Birds were once thought to have a large number of features exclusive to the group. One by one those features have also been identified in fossils of certain theropod dinosaurs. Now feathers join the list.

Among all living creatures, only birds have feathers. So when the fossil of a single isolated feather was found in the Late Jurassic rocks of Bavaria shortly after Darwin published *On the Origin of Species* in 1859, it was enough to demonstrate that, astonishingly, birds must have existed in those remote times (now known to be some 150 million years ago). When the skeleton of *Archaeopteryx* was discovered in the same area in 1861, it fulfilled that plumose prediction. But the skeleton was recognized as a bird's mainly because it had feathers on its wings and tail. Nothing else except an odd, boomerang-shaped wishbone seemed to ally it to living birds. In fact, some other specimens were assigned to *Archaeopteryx* only belatedly, because no feathers were preserved in the fossils concerned. Those specimens had instead been taken for small carnivorous (theropod) dinosaurs.

On page 753 of this issue, Ji *et al.*[1] show unequivocally that clothes don't make the bird. They describe two small theropod dinosaurs from geological beds in the Liaoning province of China[1–4]. The age of the beds is disputed; although initial reports suggested they are Late Jurassic, radiometric dates and other evidence now point to the Early Cretaceous[4] — that is, around 145 million years or maybe later. These theropods have both plumulaceous (down-like) and vaned, barbed feathers on the body, arms, legs and tail. But these animals were clearly not birds, and they were clearly not capable of flight.

One form, *Protarchaeopteryx*, has been briefly described in a Chinese journal[2]. It has down-like feathers on its body and tail, and vaned, barbed, symmetrical feathers along at least the end of the tail, in a fan-like pattern. The second, *Caudipteryx*, has remiges (primary feathers) attached to the second (longest) finger of the hand, though the arms are much shorter than in birds. These feathers are also vaned and barbed, and down-like feathers are also preserved. Were preserva-

tion more complete, we would have an even fuller idea of the plumage of these animals. This is the most that can be said at the moment, but new specimens continue to emerge from this locality.

If these are true feathers — and it can scarcely be doubted — what does this do to our conception of birds? The bottom line is that it simply forces us to revise our idea of the association of feathers with the animals we call birds. This is why.

Systematists *define* the names of organisms (taxa) by their ancestry; in this case, birds (Aves) consist of *Archaeopteryx* plus living birds (Neornithes) and all the descendants of their most recent common ancestor (Fig. 1). But we *diagnose* (recognize) birds by unique features that only they possess; these are inherited from that most recent common ancestor. (Ji *et al.*[1] give three such features, none of which relates to feathers.) So the diagnostic characteristics follow from our definition of ancestry. Why worry if feathers turn out to be shared by a wider group than birds alone? We still define birds as *Archaeopteryx* and its later relatives. *Protarchaeopteryx* and *Caudipteryx* may have feathers but they're not birds, because they're not members of that ancestral club of *Archaeopteryx* and living birds. Ji *et al.*[1] show that these animals belong to a group of dinosaurs known as the maniraptoran coelurosaurs, which include the small theropods most closely related to birds. However, their analysis of evolutionary relationships does not encompass a broader group of coelurosaurs, which might eventually help to pin down the position of *Protarchaeopteryx*.

By admitting that plumage did not first spring full-blown on the wings of *Archaeopteryx*, we are free to examine how feathers evolved in the first place. At the 1996 meeting of the Society of Vertebrate Paleontology, Dr Chen Pei-ji disclosed photographs of an amazing specimen — a small theropod dinosaur, also from the Liaoning beds, with a fringe of hair-like or down-like structures along its neck and backbone. This animal, dubbed *Sinosauropteryx* by Ji and Ji[3,4], turns out to be closely related to the basal (relatively 'primitive') coelurosaur *Compsognathus*, a chicken-sized, short-armed form found in the same deposits as *Archaeopteryx*[5]. Without even seeing the specimens, critics of the theropod–bird connection tried to pass off these remains as artefacts of preservation. They claimed that the structures were frayed internal collagen fibres, not external or epidermal in origin at all, and that similar structures in sea snakes suggested that these theropods lived in an aquatic environment[6]. Those doubts can now be put to rest[3,4].

The evolution of carnivorous dinosaurs through basal coelurosaurs into birds shows some unmistakable trends[7]. As their evolutionary history has become better known, we have seen wishbones, breastbones, hollow
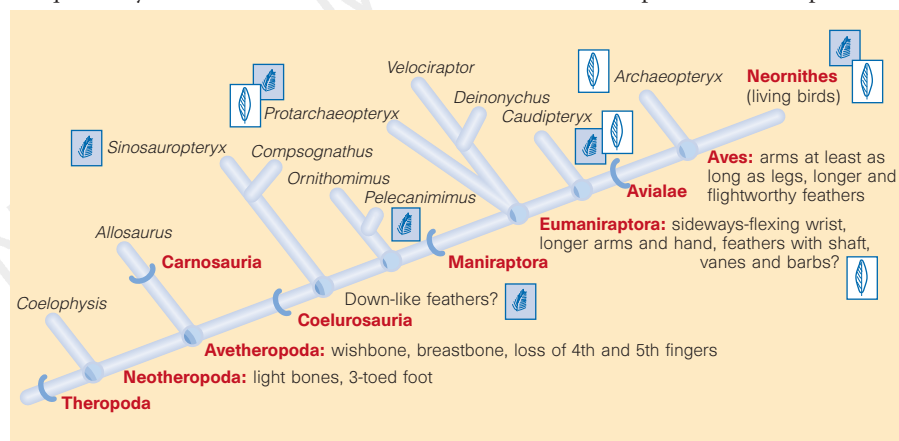
Figure 1 **Distribution of known feather types and other features in selected groups of theropod dinosaurs, including birds (Aves). The nodes (junctions) on the diagram provide the names and shared features of the groups connected above the nodes. Hence, the Avetheropoda (everything but *Coelophysis* in this diagram) have wishbones and breastbones and have lost the fourth and fifth fingers. The fossils of *Protarchaeopteryx* and *Caudipteryx* have both the vaned and down-like feathers seen in living birds, so we infer that their common ancestor (group Eumaniraptora) had them. (This may be true for the *Velociraptor*–*Deinonychus* group, by inference, unless *Protarchaeopteryx* later turns out to be more closely related to birds than they are.) Down-like feathers are not known in specimens of *Archaeopteryx*. But the base of its vaned feathers are down-like[9], like those of *Protarchaeopteryx* and living birds, and the reasonable inference is that *Archaeopteryx* did in fact possess them. *Sinosauropteryx* has only the beginnings of down-like feathers, which could be seen as an aberration or a foreshadowing of their later elaboration in the Eumaniraptora, but their similarity to down-like feathers is very strong[4]. Similar structures have been reported in the ornithomimid *Pelecanimimus*[10], but these now appear to be other soft-part structures[11].**

bones, long arms and hands, sideways-flexing wrists, nesting behaviour and rapid growth rates all disappear from the avian catalogue of exclusive features. Like feathers, as Ji and colleagues' work[1] shows, these features first evolved in coelurosaurs for purposes completely unrelated to flight[7]. The proto-feathery fringe of *Sinosauropteryx,* now known to extend to its flanks as well as along its midline[4], was obviously not made for flight and it is questionable whether it could have served any kind of function in insulation. Camouflage, display and species recognition come to mind as other possibilities[8].

Caudipteryx and *Protarchaeopteryx* go it one better, evolving long feathers with a central rachis (shaft). Were these feathers airworthy? Their vanes are symmetrical and very even, suggesting interlocking barbs, although most flying birds have asymmetrical feathers. However, the arms of *Caudipteryx* are only 60% as long as the legs, and they are only two-thirds as long in *Protarchaeopteryx* (in *Archaeopteryx* they are of more or less equal length). Evidently, the arms and feathers were not large enough for flight (the plumage is not yet known well enough to say if it was effective as insulation, or what other functions it may have served). The feathers of *Archaeopteryx* seem to be a natural extension of this trend, so to speak,

but they are not much different qualitatively. So the available evidence suggests that structurally airworthy feathers may have evolved before they were long enough, or their possessors able to use them, for flight.

The work of Ji *et al.*[1] should lay to rest any remaining doubts that birds evolved from small coelurosaurian dinosaurs. These new discoveries will excite the public and scientists alike by showing that down-like and later vaned body feathers evolved before flight feathers, and that a full complement of feathers was present in coelurosaurs before birds were invented. ☐

Kevin Padian is in the Department of Integrative Biology and the Museum of Paleontology, University of California at Berkeley, Berkeley, California 94720-3140, USA.
e-mail: kpadian@socrates.berkeley.edu

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Fullerenes

C₆₀'s smallest cousin

James R. Heath

In 1990, Kratschmer, Lamb, Fostiropoulos and Huffman (KLFH)[1] caught the chemical world off-guard when they announced their synthesis of C_{60}-buckminsterfullerene. It was surprising not only that bulk quantities of fullerenes could be prepared, but also that the process was so simple. In chemical terms, the KLFH synthesis is essentially a single-step procedure — strike an arc across two graphite electrodes and large quantities of fullerenes are produced.

In reality, however, the formation of fullerenes proceeds through an extremely fast and complex sequence of reactions, starting with carbon atoms and dimers[2]. In spite of the tremendous advances in fullerene chemistry since the initial discovery of C_{60} in 1985 (ref. 3), very little detailed insight into the formation mechanisms of the fullerenes and related structures has been achieved. On page 771 of this issue[4], Piskoti, Yarger and Zettl present evidence for the formation of bulk quantities of C_{36}-fullerene. This represents the first direct evidence that a fullerene smaller than C_{60} is produced in the KLFH synthesis. The very fact that C_{36} is formed implies much about the chemistry that leads to C_{60} and the higher fullerenes.

Most researchers agree that the arc-gen-

erated vapour of atoms and dimers initially condenses to form linear carbon chains containing from 3 to 20 atoms, and the importance of these structures was realized nearly 40 years ago[5]. The next stage in fullerene growth involves a transition, somewhere between C_{10} and C_{20}, of carbon chains into

monocyclic ring structures. Monocyclic rings have also been the subject of attention for many years, and ion-mobility measurements indicate that ring-like structural isomers may actually exist up to C_{60} or higher[6]. It is also clear that more compact structures exist for clusters larger than C_{30}, and those structures are probably the precursors to C_{60} and the higher fullerenes.

Two growth mechanisms have been proposed to explain the KLFH fullerene synthesis, and they predict very different types of structures for the C_{30} to C_{59} size range. The first mechanism, the pentagon road, postulates that three-dimensional structures containing hexagons and pentagons become important above C_{30} (ref. 7). The rule of thumb for these clusters is that the number of adjacent pentagons is always minimized, and so these structures tend to remain open as they grow. The smallest closed fullerene is the first one that can avoid adjacent pentagons, and is, of course, C_{60}.

In the second proposed mechanism, the fullerene road, three-dimensional structures containing hexagons and pentagons also become important somewhere around C_{30} (ref. 8). Adjacent pentagons are allowed along this road — it is dangling bonds that are minimized.

If a cluster has no adjacent pentagons (as in C_{60}), then it is kinetically stabilized. For the pentagon road, dangling bonds at the edge of the carbon clusters provide reactive sites for cluster growth. For the fullerene road, adjacent pentagons, which are the points of highest strain energy for a closed fullerene, provide reactive sites for growth through addition of C_2 units. Both proposed mechanisms lead naturally to large amounts of C_{60}, C_{70} and the higher fullerenes. But whereas thermodynamic arguments favour the fullerene road[9], kinetic arguments favour the pentagon road.

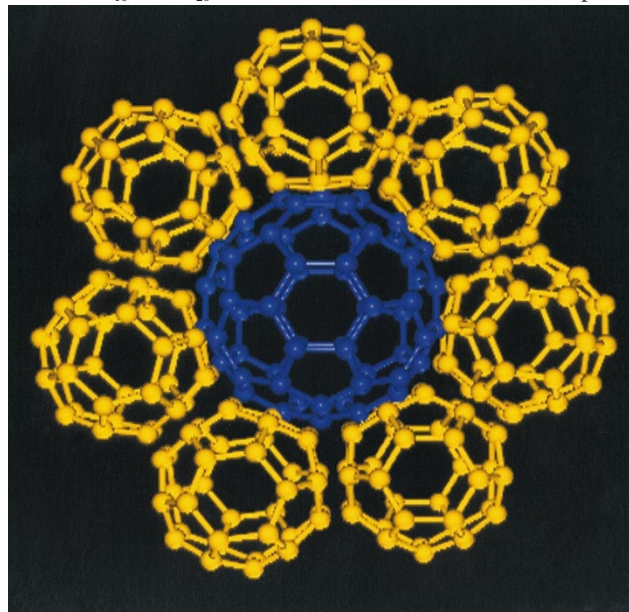Manolopoulos and Fowler[10] have predict-

Figure 1 **Little and large relations — C_{60} surrounded by seven of its smaller C_{36}-fullerene cousins, which Piskoti *et al.*[4] have prepared in bulk form. C_{36} is golden yellow in solution, whereas C_{60} is blue/purple. The apparent symmetry of C_{36} implies much about C_{60}'s chemical ancestry. In particular, C_{36} has the minimum possible number of shared pentagon–pentagon bonds, which is consistent with the growth mechanism for C_{60} known as the fullerene road. (Figure courtesy A. Zettl.)**