is in a metastable state. The simulations also showed that the metastable domino phase is stabilized when stress is applied perpendicularly to the plane of the simulated grain boundary, so that its energy matches that of the stable pearl phase — thereby establishing a true thermodynamic equilibrium between the two phases.

Meiners and colleagues' work clearly proves that phase transformations occur in the grain boundaries of pure metals, and thus opens up fresh opportunities for materials design. The number of possible polymorphs of bulk metals is generally limited, but the variety of grain-boundary structures and their possible metastable polymorphs (sometimes referred to as complexions[6]) is essentially boundless[10,11]. One can therefore envisage a processing technique that optimizes the overall performance of a material by producing grain-boundary phases (either stable or metastable) that maximize the positive effects of boundaries, but minimize their negative effects. For example, if one could produce grain-boundary polymorphs in aluminium that efficiently block dislocation glide (to maximize mechanical strength) and minimize electron scattering (minimizing electrical resistivity), the resulting metal would be a 'dream material' for making wire conductors in overhead power lines — eliminating the need for more-expensive aluminium-based composite wires.

However, it remains to be seen whether the full potential of engineering phase transformations at grain boundaries can be realized in practice. One reason is that it is not clear how processing methods could be designed that produce desired grain-boundary phases. Moreover, a similar concept known as grain-boundary engineering[12] — the use of processing methods to obtain grain boundaries that have a desired geometry and properties, without using phase transformations — has so far yielded only modest practical results.

Another issue is that the large number of possible grain-boundary polymorphs will make it difficult to systematically determine polymorph properties. High-throughput computational methods based on machine learning and big data will be of help here[1,13]. Indeed, Meiners and colleagues' work is a promising example of how the synergistic combination of high-resolution microscopy techniques and computational methods can lead to conceptual breakthroughs in the study of grain boundaries.

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Palaeontology

Poultry through time

Kevin Padian

A newly discovered 66.7-million-year-old fossil bird excavated in Belgium provides us with the best evidence so far for understanding when the living groups of birds first evolved and began to diverge. **See p.397**

The living groups of birds are amazingly diverse, numbering some 10,000 species, and endlessly fascinating. But when did they first evolve? The answer depends on how you define a bird, how you recognize the most basal (earliest diverging) birds in the fossil record, and how you account for the palaeontological and genetic gaps in our knowledge of bird evolution. On page 397, Field *et al.*[1] report the discovery of a fossil bird from 66.7 million years (Myr) ago, during the Late Cretaceous period, the most recent point in time currently known when the first representatives of today's birds evolved. In the process, the authors offer what might be a useful corrective to genetics-based estimates of the timing of bird diversification.

Most narratives of bird evolution begin with the pioneer *Archaeopteryx*, which first took wing in the Late Jurassic period (some 150 Myr ago) in present-day Germany[2]. *Archaeopteryx* is a bird in the broad sense of the term — it had a full complement of feathers and flew by flapping its wings — but it's far from having the hallmarks needed to group it with members of any living birds. *Archaeopteryx* has features that are so unspecialized that they don't prevent it from being the ancestor of all later bird groups, but they don't tell us whether living birds arose from this exact lineage.

When considering the relationships between any large group of organisms, such as birds, a key split on the evolutionary tree (Fig. 1) is the distinction between what are called crown-group and stem-group members[3]. For birds, the crown group includes all living birds (from ostriches to warblers, including quail, gulls, finches, woodpeckers, crows and all their relations), plus all descendants of their most recent common ancestor (that is, all the ancient ostriches, warblers and relatives of the other living bird groups). By contrast, the stem-group birds are those placed outside the living groups of birds but nevertheless still closer to them than they are to other major related groups, such as extinct dinosaurs: in other words, birds from *Archaeopteryx* (the most basal known bird) up to, but not including, living bird groups. The question is whether Field *et al.* are reporting on another stem-group bird or the first well-established crown-group bird, and what the age of their fossil discovery tells us about the timing of avian evolution.

All available evidence indicates that birds evolved from a group of carnivorous dinosaurs called theropods during the Jurassic period (about 200–145 Myr ago), and that bird flight had evolved by then, at least considering *Archaeopteryx*[2]. Through the Cretaceous period (145–66.5 Myr ago) there was considerable evolutionary experimentation in the early offshoots of bird lineages (in such diverse groups as the Enantiornithes, Hesperornithes and Ichthyornithes)[4]. But these ancient birds are outside the crown group because they lack the structural and physiological features characteristic of living birds. These stem-group birds seem to have grown much like small dinosaurs had done ever since the Triassic period (about 250–200 Myr ago) — faster than typical reptiles but slower than today's birds, reaching maturity in a few years, on the basis of examination of their bone tissues[5].

However, sometime during the latest Cretaceous, a stem-group lineage of birds evolved that had much higher growth rates than these more basal lineages, and that generally matured within a year or even sooner[2,5]. These became the crown-group birds. Their relationship to the closely related stem-group birds remains fuzzy, partly because fossil birds are

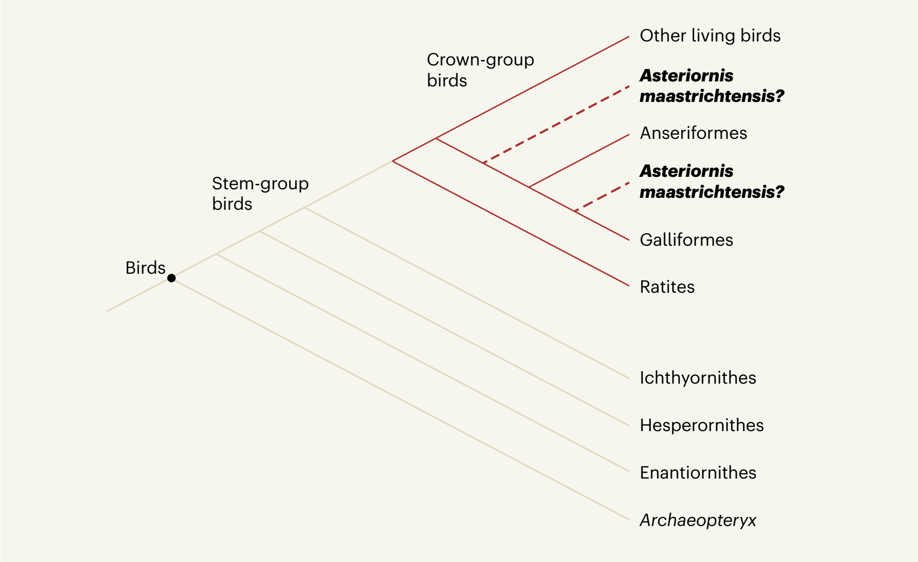

Figure 1 | An evolutionary tree for birds. Birds can be divided into crown-group birds (all living birds plus all relatives of their most recent common ancestor) and stem-group birds, which fall outside this group but are closer to it than they are to other major related groups, such as the dinosaurs ancestral to birds. Fossils of stem-group birds include specimens of *Archaeopteryx*, Enantiornithes, Hesperornithes and Ichthyornithes. Such stem-group creatures had wings, but lacked some hallmarks of crown-group birds. Field *et al.*[1] report the discovery of a 66.7-million-year-old crown-group fossil bird that they call *Asteriornis maastrichtensis*. This fits on the tree near Anseriformes (duck- and goose-like birds) and Galliformes (chicken- or quail-like birds), but the fossil remains are insufficient to determine whether it is closer to the Galliformes than to the Anseriformes, or whether it is outside the group formed by Galliformes and Anseriformes. Regardless of this, the fossil reveals that the duck and chicken lineages, together with the mostly flightless birds called ratites (such as ostriches) plus other living bird lineages, had evolved by at least 66.7 million years ago. Earlier examples of crown-group birds are, as yet, unknown.

usually rare and poorly preserved[4].

This issue underlies the importance of the fossil bird reported by Field and colleagues. Although some previously discovered specimens have helped to pinpoint the ultimate origin of living birds, the authors' discovery is the best evidence yet of when and how the first known crown birds evolved. Field and colleagues named their Belgian fossil specimen *Asteriornis maastrichtensis*. It is from the latest Cretaceous period, and was relatively small (with an estimated body weight of about 400 grams).

The remains are confined to an excellently preserved skull and some other fragmentary bones (see Fig. 1 of ref. 1), which is enough to establish not only that it is a crown-group bird, but also that it is an early member of the group of land birds called Galloanserae. Think of this group informally as 'poultry': chickens, quail and the like (Galliformes), plus ducks, geese and so on (Anseriformes). *Asteriornis* seems to be a basal member of this group and possibly (Fig. 1) on the chicken–quail branch (Galliformes), but the available information is too scarce and fragmentary for scientists to be sure. Most other known ancient specimens of fossil bird are either well-established members of living groups or outside this crown group entirely[4]. The position of *Asteriornis* on the bird family tree is particularly interesting because, among crown birds, the first major branch that diverged from the others (Fig. 1) is the ratites (most of which are flightless birds, including ostriches)[6,7] — so *Asteriornis* is, if you'll forgive the expression, well nested within the crown group of birds.

What does the age of this *Asteriornis* fossil tell us about the timing of avian diversification? It's only one bird, so it doesn't reveal much about that. But we know that this specimen was on the scene about 200,000 years before the end of the Cretaceous. That establishes that crown-group birds evolved before the end of the Cretaceous, but perhaps only barely before then.

> **"Fossil remains are a crucial test of molecular-based projections of evolutionary divergence times."**

This is something of a corrective to the conventional estimates of the earliest origin and diversification of living bird groups based on molecular phylogenetic analyses, which have proposed estimates of this divergence timing ranging from 139 to 95 to 89 Myr ago (to mention just a few such studies)[8–11]. If these values seem all over the place, let's remember that such studies usually analyse changes in DNA sequences for a few genes and assume that the rate of molecular evolution is relatively constant over time. The very effort that such work takes to resolve these evolutionary divergences with such indirect molecular evidence is heroic.

Why should palaeontological evidence be 'smarter' than molecular evidence in cases such as this? Fossil remains are a crucial test of molecular-based projections of evolutionary divergence times. If a molecular study estimates a given age of origin for a group, then fossils from the corresponding timeframe should have the diagnostic features that identify those groups. If fossils from the time of interest provide no evidence of the expected newly evolved features, then the molecular projections are not supported. The evidence for *Asteriornis* reported by Field and colleagues implies that crown-group birds first evolved when the Cretaceous period was nearly over. That places a strong constraint on hypotheses for basal divergence times, but there will always be more fossils to find.

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