light, but the transmitted light also undergoes a geometric Pancharatnam–Berry phase delay — a change in phase that depends on the orientation of the optic axis of the liquid crystal. Because of the way in which the optic axes are orientated within the droplets, laser beams emerge with a helical wavefront (Fig. 1b), and hence with an orbital angular momentum. Pancharatnam–Berry phase delays have previously been used in macroscopic light-mode converters based on liquid crystals[7], but never before has the effect been a natural consequence of microscopic droplet structure.

A surprising feature of Brasselet and colleagues' microscopic converter is that it works over a wide range of optical wavelengths — a feat previously made possible only using combinations of optical components[8]. In their present form, however, the inherent structure of the droplets[2] means that the resulting beam contains only two intertwined wavefronts, whereas traditional approaches can generate any number of them. The challenge now will be to extend the droplet approach to yield larger numbers of intertwined wavefronts, and to construct a robust, miniature converter that can be used in practical applications. Given the apparent purity of the beams produced using Brasselet and colleagues' strategy, this is a challenge well worth pursuing. ■

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PALAEONTOLOGY

Feathered dinosaurs in a tangle

Lawrence M. Witmer

A dramatic feathered dinosaur fossil from the Jurassic of China resolves a 'temporal paradox'. But it adds intriguing complications to the debates on the evolution of feathers and flight in birds.

Birds are dinosaurs. That's hardly the stuff of headlines any more, as data have streamed in revealing anatomical similarities between birds and the theropod dinosaurs from the tips of their noses to the tips of their feathered tails. More elusive have been the details of the transition to birds and the evolution of flight. On page 640 of this issue, Hu and colleagues[1] present a spectacular new specimen of the feathered theropod *Anchiornis huxleyi* that solves some problems. But it simultaneously creates new ones, revealing what a gloriously messy business it is to tease apart the evolutionary tangles that we retrospectively anoint as an 'origin'.

Anchiornis is a small, crow-sized theropod, assigned to a group known as the troodontids (Fig. 1), which in life was covered with long bird-like feathers. The new fossil, like other, more poorly preserved specimens, was collected from the Tiaojishan Formation of Liaoning, China. Liaoning Province has yielded many specimens of feathered theropods and true birds[2], and so it might seem that yet another feathered dinosaur shouldn't merit much attention. But what's important about the fossils of *Anchiornis* is their age — they are from the Jurassic period, and at about 155 million years old are much older (by about 25 million to 35 million years) than the other feathered Liaoning theropods, which come from Early Cretaceous rocks. Even more significantly, *Anchiornis* is older (by 5 million to 10 million years) than the iconic 'first bird' *Archaeopteryx*, which comes from younger Jurassic rocks in Germany.

One lingering problem with the hypothesis that birds descended from dinosaurs had been that the most bird-like theropods occurred later in time than did *Archaeopteryx*. It has been argued that this 'temporal paradox' (how can a 'descendant' arise before an 'ancestor'?) both invalidates the theropod ancestry of birds[3] and, reversing the ancestor–descendant relationship, suggests that some of the Cretaceous bird-like theropods actually descended from Jurassic *Archaeopteryx*-like birds[4,5]. In truth, the temporal paradox never seriously challenged the theropod hypothesis, because it essentially assumed that fossils like *Anchiornis* wouldn't be found — arguments based on negative evidence are always dicey. However, the notion of some Cretaceous theropods being secondarily flightless descendants of early birds remains a valid hypothesis given the common and repeated evolution of flightlessness in birds[6].

Anchiornis resets that whole debate. By predating *Archaeopteryx*, *Anchiornis* shows that bird-like feathered theropods were around 'early enough' to serve as ancestors, although no one is suggesting that *Anchiornis* itself was that ancestor. Thus, there is no temporal paradox. At the same time, the idea that some Cretaceous theropods might be flightless descendants of early birds can now be assessed on the basis of evidence rather than being mandated by temporal congruence. But *Anchiornis* does more than refute the temporal paradox, in that the distribution of feathers on its body suggests that we now need to revise our thoughts on the evolution of flight.

In 2003, the description of *Microraptor gui* as a 'four-winged dinosaur'[7] rocked the palaeontological world. This creature, a basal member (that is, on an early-branching twig) of a different theropod lineage, the dromaeosaurids, had elongate, bird-like feathers not just on its arms but also on its legs and feet. This find was entirely unexpected in that, although feathered forelimbs and tails had been reported in various non-avian theropods, there was little reason to suspect that elongate pennaceous feathers (that is, with shaft and vanes, as in the flight feathers of living birds) occurred on the legs, let alone the feet. Later, elongate feathers were found on the legs and feet in *Pedopenna*, a basal member of the avialans, the group that includes *Archaeopteryx* and other birds[8].

Anchiornis, a basal troodontid, also has long feathers on its legs and feet to match those on its arms and tail, so the family Troodontidae now joins the Dromaeosauridae and Avialae

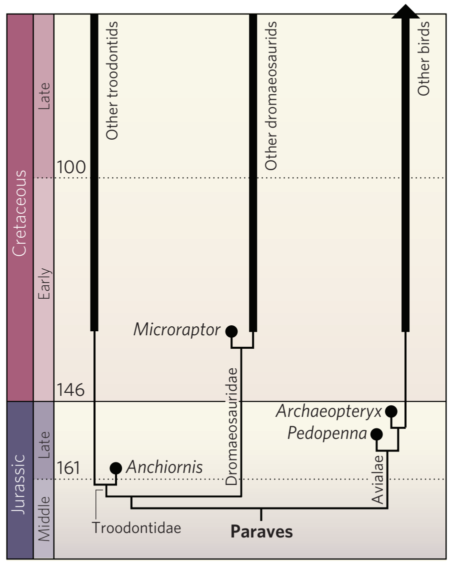

Figure 1 | *Anchiornis huxleyi* in context. The fossil described by Hu *et al.*[1] is assigned to the family Troodontidae, which together with the closely related Dromaeosauridae and Avialae comprise the Paraves (itself a subgroup of the theropod dinosaurs). One significant aspect of *Anchiornis* is that it predates *Archaeopteryx*, the iconic 'first bird', by some 5 million to 10 million years. Another is that it shows that basal members of all three of the Paraves groups — *Anchiornis*, *Microraptor* and *Pedopenna* — had long pennaceous feathers on their lower legs and feet, as well as on their hands and tail. The implication is that avian evolution conceivably went through a 'four-wing' stage. Numbers are approximate ages of the geological divisions in millions of years ago.

on the list of theropods with 'hind wings'. Among modern birds, only a few species have long feathers on their legs (the tibiotarsal region), and none has long, aerodynamically relevant feathers on their feet. So palaeontologists have been scrambling to make sense of what feathered legs and feet in basal birds and dromaeosaurids mean for the evolution of flight.

When we just had *Microraptor*, it was easier to dismiss the long foot feathers as potentially a mere early experiment in aerodynamics that was independent of the evolution of avian flight[9,10]. And indeed, it potentially biases the functional argument to refer to these elongate leg and foot feathers as 'flight feathers' that formed a lift-generating 'hind wing', in that other functions are conceivable[9] (such as display). Still, these elongate feathers would have had aerodynamic effects even if they had not evolved originally as flight adaptations, and credible aerodynamic models have been proposed[10]. But *Anchiornis* shows that *Microraptor* was no one-off, and that basal members of three separate theropod groups had long foot feathers.

This association of Troodontidae, Dromaeosauridae and Avialae is no chance occurrence. These groups together form a branch of the theropod evolutionary tree known as Paraves — they're each other's closest relatives (Fig. 1). The fact that basal members of all three groups had long pennaceous feathers on their lower legs and feet strongly suggests that the paravian common ancestor also had feathered feet. It's not at all certain yet whether these feathers comprised an aerodynamically competent flight surface that provided lift and/or thrust. But it's hard to imagine that they wouldn't have had some aerodynamic effects (drag, for instance).

More to the point, it now looks as if we'll have to accept that avian evolution indeed went through — at the risk of overstatement — a four-wing stage, only to eventually lose the long foot feathers. What this means for the evolution of the avian flight stroke[9] is now an open question. Likewise, we'll need to seriously consider how these otherwise seemingly very adept and agile runners (*Anchiornis* has extremely long and slender hindlimbs) could manage with long feathers on their feet.

Even apart from feathers and aerodynamics, Hu and colleagues' analysis[1] of *Anchiornis* reveals just how similar these early paravians were to each other: the basal members of each of the three groups seem to mix-and-match their anatomical similarities, so that their unique attributes are becoming more and more subtle. It's getting hard to tell members of one group from another. On the bright side, in this year of Darwin, that fact provides a comforting affirmation of the evolutionary prediction that species in different groups will become increasingly similar as we approach their common origin. ■

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SUPRAMOLECULAR CHEMISTRY

Molecular crystal balls

Seth M. Cohen

Sorcerers have long gazed into crystal balls to conjure up information. Chemists are also getting in on the act, using porous crystals to trap unstable reaction intermediates and to reveal their structures.

The reactions of molecules with one another often proceed through intermediates before the final products are formed. Such intermediates are frequently short-lived and unstable, which restricts our ability to characterize them. Typically, the identification of such fleeting species is limited to fast, time-resolved spectroscopic measurements. But in this issue (page 633), Kawamichi *et al.*[1] report that they have trapped an unstable chemical intermediate in a porous crystalline material, and were thereby able to characterize the structure of the intermediate unambiguously by X-ray crystallography. The authors suggest that such porous crystals can act as protective matrices within which chemical reactions can be performed, allowing us to peer into the details of reaction mechanisms in an unprecedented way.

Kawamichi *et al.* examined a reaction familiar to every student of organic chemistry: the combination of an amine and an aldehyde to form a Schiff base (Fig. 1a). Although the mechanism of this fundamental reaction has been extensively studied, direct observations of the ephemeral intermediate — a hemiaminal — are rare. The crystal structure of a hemiaminal trapped in the active site of an enzyme has been reported[2], but structure determination in protein crystals is not a general approach for characterizing reaction intermediates.

The authors[1] use a 'coordination network' of organic ligand molecules and metal ions to trap the elusive hemiaminal. Coordination networks — also known as porous coordination polymers or metal–organic frameworks — are solid, crystalline materials that generally

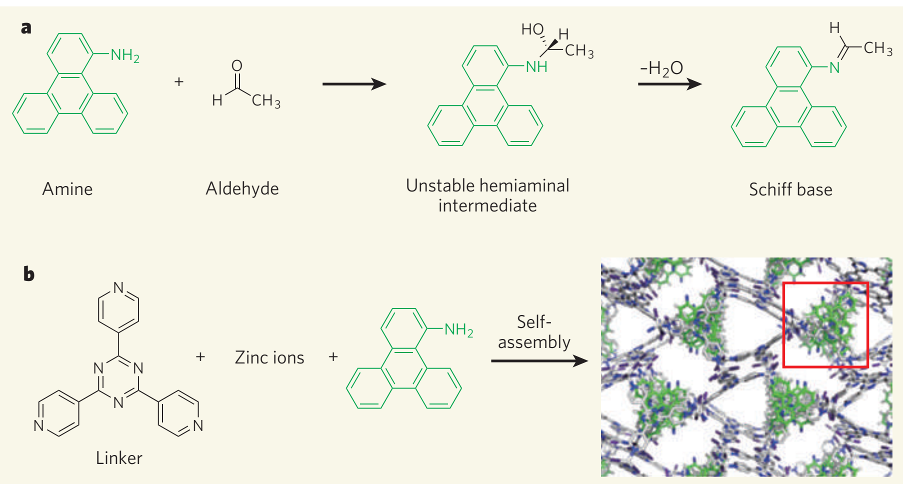

Figure 1 | Caught in a trap. a, Kawamichi *et al.*[1] have stabilized and observed the crystal structure of an elusive hemiaminal intermediate that is transiently formed during the reaction of an amine and an aldehyde to form a Schiff base. **b**, They did this by performing the reaction within the restrictive and orderly confines of a crystalline coordination network (a cage-like molecular structure) at low temperatures. The authors trapped amine reactants as guest molecules in the network as it self-assembled from its constituent parts — organic 'linker' molecules and zinc ions that act as nodes between the linkers. In the network structure, the amines are shown in green, and one is highlighted in the red box.