

weight, did not flower and died soon after the emergence of the broomrape flowering stalk.

The doubled yields afforded by control of the parasites will more than offset the added cost of both the transgenic seed and the small amount of herbicide, even in underdeveloped countries. This approach should only be used with crops that do not interbreed with related weeds in the same locality. The use of such transgenics represents a necessary stopgap measure until other means are found, as resistance can rapidly evolve to

some of these herbicides (such as the ALS inhibitors), but is expected to evolve more slowly to the others<sup>2</sup>.

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## Feather asymmetry in *Archaeopteryx*

SIR — After comparing flight feather asymmetry of *Archaeopteryx* with the asymmetry of several extant birds with various flight styles, 'flapping', 'gliding' and 'flightless', Speakman and Thomson<sup>1</sup> claim that *Archaeopteryx* was not capable of sustained flapping flight. In my view, their analysis is flawed and does not support their conclusion.

First, they report asymmetry values for *Archaeopteryx* feathers that are far too low, and they make a misleading comparison with extant birds. I have examined high-quality photographs in two fold-out plates<sup>2</sup>, showing the left and right wing of the Berlin *Archaeopteryx* specimen at 2.8 and 4.1 times their natural size. The first three feathers are staggered in length, so the anterior margin is entirely free and clearly visible all along the outer half of feathers 1 and 2 in both wings. Also, feather 3 of the right wing has its anterior margin free in the outer part that extends beyond feather 2. The photographs show the ventral side of the wing, so, because of the way feathers are arranged in a bird wing, the rear margin of these feathers is also free and unobscured. At about 25% of the feather length from the tip, the feather shaft of the four anteriormost primary feathers (1–4) is located 24–34% of the feather chord behind the leading edge; thus, the trailing-vane is 3.11–1.91 times as wide as the leading-vane. This is much more asymmetrical than 41% of the chord behind the leading edge, or the ratio 1.46, reported by Speakman and Thomson for primary feathers 4, 5 and 6 of the Berlin specimen.

My asymmetry values are near the lower limit of, but partly inside, the range for 'flapping' and 'gliding' birds (Fig. 2 in ref. 1). Further, Speakman and Thomson's values for extant 'flapping' and 'gliding' birds are from primary feathers 1 or 2, which are more asymmetrical than feathers further back (Fig. 1 in ref. 1), but they nevertheless compare them with primaries 4, 5 and 6 in *Archaeopteryx*. I therefore conclude that the feather asymmetry of *Archaeopteryx* is within the range of modern birds using flapping flight.

Second, on the wing's downstroke, the

anteriormost primary feathers of modern birds often separate so that the outer part of each one acts as an aerofoil on its own<sup>3</sup>. The vane asymmetry then comes into operation and effects a proper orientation of the feather to the incident air stream. On random changes of angles of attack, the aerodynamic centre of pressure of a flat plate, or feather, does move fore and aft in such a way that it maintains dynamic stability in pitch, and hence in angle of attack, provided that the span-wise torsion axis lies within the interval 27–35% of the chord length behind the leading edge<sup>4</sup>. The feather shaft acts as a local torsion axis in any chord-wise profile. When the feather shaft lies ahead of the 27% chord point, there is a nose-down pitch moment that also tends to match the angle of attack to the incident air-stream.

The crucial feature of *Archaeopteryx* feather asymmetry is that the shaft of the anteriormost primary feathers is 24–34% of the chord behind the leading edge, completely ahead of the critical rear limit 35%, as required for self-stability in pitch. Consequently, vane asymmetry in *Archaeopteryx* primary feathers is pronounced enough to confer automatic pitch control on separated feather tips, and therefore does not indicate a lack of powered flight.

The asymmetry of the first three primaries is what matters most. Because of their staggered length in *Archaeopteryx*, they all form part of the wing's leading edge and therefore they are the feathers most likely to split apart in flight, acting as aerofoils — actually, leading-edge slats — on their own, with a need for the automatic pitch control that the vane asymmetry gives.

Third, the function of vane asymmetry is linked to the function of feather curvature<sup>3</sup>. Flight feathers in bird wings are per-

manently bent backwards and the feathers are free to rotate in the nose-up sense in their sockets. Nose-down rotation is prevented by the feathers' attachment in their sockets. It is also restricted by the nearest-neighbouring feather lying behind it, and partly overlapping the upper side of the trailing vane, so that the feathers are pressed together on the down-stroke. As a result of feather curvature, and less of vane asymmetry, the flight feathers of modern birds rotate in the nose-up sense on the upstroke when this is aerodynamically non-functional, letting air through the wing. This rotation occurs about an axis through the feather base, and because of the shaft curvature, most of the feather vane is behind this axis to provide the required nose-up torque.

*Archaeopteryx* flight feathers are as strongly curved as those of modern birds<sup>3</sup>. Its feather curvature alone could therefore provide the nose-up moment required for individual feathers to rotate about the axis through the feather base to let air through the wing on the upstroke. Also, the vane asymmetry in *Archaeopteryx* is pronounced enough to prevent a counteracting nose-down moment to be set up about the local feather shaft on the upstroke. Feather curvature and vane asymmetry in *Archaeopteryx* are therefore fully consistent with an active, flapping, flight mode.

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SPEAKMAN AND THOMSON REPLY — Norberg raises several interesting but erroneous comments.

(1) He has measured vane asymmetry for one *Archaeopteryx*. His measurements exceed those made by us<sup>1</sup> on two specimens. Unfortunately, many of his measures were made on regions of the feathers which are overlapped. Since measuring asymmetry depends on defining both feather margins, his measurements depend critically on a subjectively inferred position of the hidden margin. Different observers have inferred asymmetry ( $a_p$ ) for the overlapped feathers of *Archaeopteryx* ranging from complete symmetry<sup>5</sup> ( $a_p = 1.0$ ) to extreme asymmetry<sup>6</sup> ( $a_p$  is approximately 4–5 from Fig. 1 in ref. 6). Our measurements are more accurate as they were made on sections of the feathers which do not overlap. The measures he made which were not overlapped refer to the diminutive first and second primaries; these small feathers would not be important in flight. In our measurements of extant birds we ignored the first primary when it was diminutive (less than half the length of the second primary); thus, comparing the diminutive primaries of *Archaeopteryx* to our sample of extant birds is invalid.

### Scientific Correspondence

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