Stockholm University, Sweden.
e-mail: adan@us.es

1. Pawłowski, M. *et al. Nature* **461,** 1101–1104 (2009).
2. Oppenheim, J. & Wehner, S. *Science* **330,** 1072–1074 (2010).
3. Lapkiewicz, R. *et al. Nature* **474,** 490–493 (2011).
4. Weihs, G. *et al. Phys. Rev. Lett.* **81,** 5039–5043 (1998).
5. Matsukevich, D. N. *et al. Phys. Rev. Lett.* **100,** 150404 (2008).
6. Rowe, M. A. *et al. Nature* **409,** 791–794 (2001).
7. Hasegawa, Y. *et al. Nature* **425,** 45–48 (2003).
8. Kochen, S. & Specker, E. P. *J. Math. Mech.* **17,** 59–87 (1967).
9. Cabello, A. *Phys. Rev. Lett.* **101,** 210401 (2008).
10. Kirchmair, G. *et al. Nature* **460,** 494–497 (2009).
11. Amselem, E. *et al. Phys. Rev. Lett.* **103,** 160405 (2009).
12. Cabello, A. *Phys. Rev. Lett.* **104,** 220401 (2010).

AERODYNAMICS

The cost of flight in flocks

There are well-known aerodynamic and energetic benefits to flying in an orderly formation. By contrast, it seems that the flocking flight seen in pigeons is metabolically expensive. So why do they do it? See Letter p.494

GEOFFREY SPEDDING

Formation flight has long been known to confer aerodynamic advantages on appropriately spaced fixed-wing aircraft. Flying with a wing positioned in an updraft is a little like finding a free source of lift, which, in turn, reduces drag. Drag is directly related to fuel consumption, so formation flight in birds is seen as a way for these creatures to increase their migratory range or cut the costs of general commuting. All a bird must do to reap the rewards of formation flight is stay in formation. The potential benefits of the V-formation[1] or of certain more complex clusters[2] have been noted in idealized mathematical models. However, many bird flocks apparently lack the order and precision required to make such energy savings, and it is far from obvious how to formulate a tractable theoretical model for such complex patterns.

On page 494 of this issue, Usherwood *et al.*[3] describe how they made the first measurements of body accelerations in individual birds involved in voluntary, loosely formed flocking flights. The reasonable inference from the assembled data is that such flights do not save energy, but rather come at a cost. Energy saving is not of overriding importance in such flight excursions, and the flocks must form for other reasons.

Forty years ago, Lissaman and Shollenberger[1] pointed out that the aerodynamic advantages of formation flight could be especially accessible to birds: local wing twist and wing flexibility allow these animals to configure their aerodynamic profile according to the local air-flow field. The positioning accuracy required seemed reasonable, and the stable and preferred shape of V-formations was explained as the best configuration for evening out the drag distribution in a flock. Planar V-shaped formations, as observed in migrating geese for example (Fig. 1), could increase migratory range by as much as 70%; similar energetic advantages have been proposed for fish schooling[4]. And the potential cost savings in full-scale aircraft[5], and in fleets or swarms of unmanned autonomous vehicles in the air or underwater, are topics of renewed interest.

Noting that bird flocks are not always in neat, linear arrays, Higdon and Corrsin[2] analysed a more general cluster formation. In contrast to Lissaman and Shollenberger[1], they ignored details of the air-flow distribution on the wing, and replaced each bird with a mathematically convenient function, with almost identical far-field properties. They showed that, in three-dimensional flocks, drag savings could be either positive or negative, depending on the spanwise or vertical positions of the flock members. Their tentative conclusion was that "improved flight efficiency is not an important reason for migration in large, three-dimensional flocks".

There are many possible reasons for flying in a flock, which may include mutual observation, collective guidance and navigation, enhanced security as a result of greater numbers of individuals or of eyes, fitness display, and assessment of group numbers. Energy saving may be of paramount, or little, importance. Even if energy saving is not an explicit goal, then avoiding excessive energy

N. TAYLOR WILDLIFE/ALAMY

S.-E. ARNDT/PHOTOLIBRARY.COM

Figure 1 | Flight formations and clusters. Canada geese migrate in a characteristic V-formation (left); such an orderly, planar arrangement can reduce drag, resulting in energy savings. Complex swirls and flocks of organisms, such as those of pigeons (right), have less apparent order, and in their research with pigeons Usherwood *et al.*[3] find that flocking flight patterns are energetically costly. Group travel in flocks (birds), schools (fish) and herds (large vertebrates) is common, but there are probably several, often overlapping, reasons for such behaviours.

cost may at least be a consideration.

Usherwood *et al.*[3] measured the wing-beat frequency and body accelerations of 18 trained racing pigeons when they left their home loft in voluntary excursions, which involved quite irregular clusters with varying densities and flight paths. Quite often the cluster would circulate in a tight circle or spiral. Backpacks containing Global Positioning System equipment relayed data back at rates sufficient to correlate wing-beat and body accelerations with flock position and density.

Several interesting observations followed. First, sharp turning manoeuvres, with centrifugal accelerations comparable to gravitational acceleration, are themselves costly. Second, pigeons flap their wings faster when in a cluster than when flying alone. Third, the flapping frequency correlates strongly with the proximity of neighbouring birds. The authors[3] argue that the average aerodynamic downdrafts are probably comparatively small, and propose that the high-frequency flapping is more likely to be an adaptation to increased demands on flight control and collision avoidance. Regardless of the cause, because the flapping frequency can be very roughly used as a surrogate for power consumption, the implication is that flying in such a flock is more costly than flying alone.

The dynamics (social and physical) of flying in flocks is not easy to simplify. Even in seemingly orderly flocks of pelicans or geese, the measured precision in wingtip–wingtip spacing is often quite far from the mathematical ideal[6,7]. This study[3], like most others, ignores the effect of the complex wake disturbances that are undoubtedly generated by each pair of flapping wings. Yet the empirical evidence suggests that, because energetic savings are negative, in this instance we may have to search elsewhere for the reasons for flying in flocks. Perhaps the episodic flights of racing pigeons allow the birds to test and exercise their locomotory and control machinery. As with many problems in biology, it is quite possible that more than one reason conspires to create any given bird flock. ■

Geoffrey Spedding *is in the Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, California 90089-1191, USA.*
e-mail: geoff@usc.edu

1. Lissaman, P. B. S. & Shollenberger, C. A. *Science* **168,** 1003–1005 (1970).
2. Higdon, J. J. L. & Corrsin, S. *Am. Nat.* **112,** 727–744 (1978).
3. Usherwood, J. R., Stavrou, M., Lowe, J. C., Roskilly, K. & Wilson, A. M. *Nature* **474,** 494–497 (2011).
4. Weihs, D. *Nature* **241,** 290–291 (1973).
5. Ray, R. J., Cobleigh, B. R., Vachon, M. J. & St John, C. AIAA Flight Mechanics Conf. Exhibit, Monterey 2002–4492 (2002).
6. Hainsworth, F. R. *J. Exp. Biol.* **135,** 431–444 (1988).
7. Cutts, C. J. & Speakman, J. R. *J. Exp. Biol.* **189,** 251–261 (1994).

ORGANIC CHEMISTRY

Triumph for unnatural synthesis

Nature crafts many molecules from common precursors, but this approach isn't always possible in chemical synthesis. A strategy for synthesizing a family of natural products succeeds by ignoring nature's blueprint. SEE ARTICLE P.461

STÉPHANE QUIDEAU

Polyphenols are a group of structurally diverse compounds found in fruits, vegetables and plant-based food products such as tea, wine and chocolate. Because many polyphenols are antioxidants, they have been acclaimed as natural health-protecting agents, although the benefits to humans have yet to be proven. Nevertheless, some polyphenols have biological activities that make them potentially useful leads in the search for drugs against illnesses such as heart disease, cancer and Alzheimer's disease. Pharmaceutical research has been thwarted, however, by the fact that the most complex polyphenols are available from their natural sources in only limited quantities.

An obvious solution would be to prepare large quantities of polyphenols using chemical synthesis. This might seem a trivial task, given that many polyphenols are oligomers derived from just one or two precursor molecules, of which resveratrol (Fig. 1) is perhaps the best-known example. In fact, the structural complexity of resveratrol oligomers makes their chemical synthesis a daunting challenge. But on page 461 of this issue, Snyder *et al.*[1] describe a major advance in polyphenol research: a daring but clever synthetic strategy that has enabled them to prepare a series of resveratrol trimers and tetramers — the highest-order resveratrol oligomers prepared to date.

Traditionally, strategies for total synthesis target one specific, naturally occurring compound, rather than a series of biosynthetically or structurally related compounds. Furthermore, the large number of steps involved in many classical total syntheses often makes the synthetic routes economically unviable for industrial-scale processes. Synthetic organic chemists are therefore now using their *savoir faire* to devise short, practical natural-product syntheses, with the additional challenge of finding routes that have minimal impact on the environment. One approach is to identify better ways of exploiting the inherent chemical reactivity of starting materials and/or synthetic intermediates[2]. This is the approach used by Snyder and colleagues[1], although the resveratrol oligomers that they have made are not traditional targets for total synthesis — indeed, only a few chemists have attempted to make complex plant polyphenols[3,4].

Although most polyphenols are biosynthetically derived from the metabolism of only one or two parent molecules, the structural diversity generated within each class of polyphenol is enormous[5]. A couple of hundred oligomeric constructs are known to be derived from resveratrol, for example[6]. The biosynthesis of these compounds presumably involves the initial dimerization of resveratrol (which can produce several structurally different dimers), structural rearrangement of the dimers and then further transformations to make higher resveratrol oligomers. But biomimetic strategies that involve making resveratrol oligomers by treating resveratrol with chemical or enzymatic oxidants have generally produced low yields of the desired products and/or led uncontrollably to complex mixtures of compounds.

Nevertheless, a few dimeric members of the resveratrol oligomer family have been made using molecular building blocks other than resveratrol. But none of those syntheses, elegant though they may be[7], provides a common route that could generate multiple, structurally very different members of the family. This is what Snyder *et al.*[1] have achieved.

Snyder's group previously reported[8,9] the synthesis of several different resveratrol dimers from a common building block that is distinct from, and much more chemically controllable than, resveratrol (Fig. 1). To reach the next level of complexity[1] (trimers and tetramers), the authors decided to try to attach bromine atoms to specific sites in some of the previously prepared dimeric compounds. Once installed, the bromine atoms could be used as 'handles' to introduce resveratrol-based groups known as *trans*-dihydrofurans, making trimers (by the addition of one *trans*-dihydrofuran) or tetramers (by adding two *trans*-dihydrofurans). This ambitious goal required the means not only to differentiate selected sites for bromination from all the other sites that shouldn't be brominated, but also to selectively brominate different positions in compounds at will, as required for the particular trimer or tetramer being targeted.