wing. A beautiful tip vortex is visible, as is a strong downwash behind the wing, and lateral flow (from the base of the wing towards the tip) is seen along the rear two-thirds of the wing's upper surface (Fig. 2). The leading-edge vortex is also clearly present. However, it does not have the helical structure of the hawkmoth vortex, and fluid within the vortex does not flow significantly from the wing's base to its tip. This finding is noteworthy: leading-edge vortices on flapping wings are unstable and tend to break away, causing a rapid loss of lift. Visualization of smoke trails over the hawkmoth wing[6] suggested that leading-edge vortices are stabilized by strong lateral helical flow, but this is not apparent on the robofly wing.

So how might robofly stabilize these vortices? To investigate the problem, Birch and Dickinson eliminated all lateral flow by attaching teardrop-shaped fences perpendicular to the wing surface, with the fattest portion of the teardrop at the leading edge. Such fences should block any lateral flow and, if the present view of leading-edge vortices[6] is correct, should result in decreased lift. But the opposite occurred: the lift forces actually increased slightly when the fences were present. This makes it unlikely that insect equivalents of robofly — fruitflies — stabilize leading-edge vortices by lateral helical flow, and suggests that these vortices could actually grow larger before becoming unstable. Although there is considerable variability, the bodies of most insects are 2 to 4 millimetres long, equivalent to fruitflies. We must seek other mechanisms of vortex stabilization for such insects.

In the future, by changing the viscosity of the mineral-oil bath and the shape of the wings, it should be possible to use robofly to reveal the flow and force patterns around insects with longer wings, 2 to 5 centimetres long. Modification of robofly and the flapper to a state equivalent to forward flight would also be valuable. Ultimately, however, it may be possible to integrate DPIV with micro-electromechanical-systems technology, allowing simultaneous measurements of flow and force around freely flying insects. Then the insects themselves can tell us if our models are correct. ■

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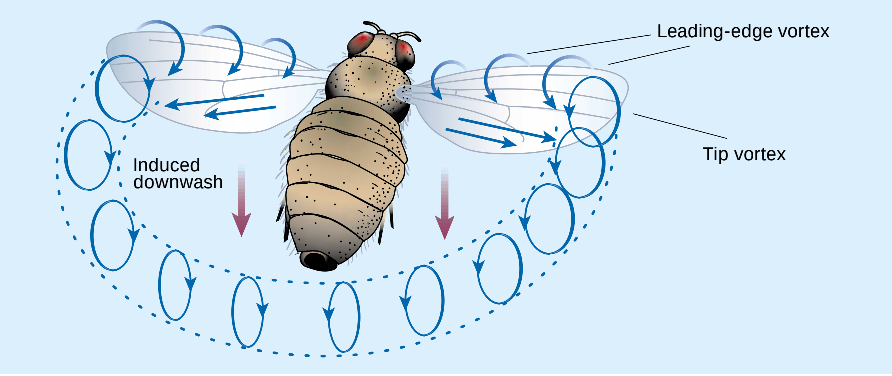

Figure 2 **Patterns of airflow during the downstroke of a hovering insect, as revealed by Birch and Dickinson's quantitative analysis[1] of fluid flow over the wing of robofly. Airflow over the leading edge of the wing rolls up into a leading-edge vortex (LEV). LEVs contain a low-pressure core that enhances lift, but they are unstable and tend to detach, causing a rapid reduction in lift. This has prompted research into how insects stabilize LEVs during flight. One proposed mechanism is the lateral flow of air from the base to the tip of the wing[6]. However, when Birch and Dickinson installed barriers to lateral fluid movement on the robofly wing, an increase in lift occurred, suggesting that, for insects of fruitfly size, mechanisms other than lateral air movement must stabilize LEVs. The presence of a strong vortex at the wing tip and downwash behind the wing may stabilize LEVs by reducing the effective angle of wing attack (the angle between the wing and the oncoming air).**

Quantum physics

Cooperation includes all atoms

Juha Javanainen

Atom statistics is a fundamental property of all particles that dictates how they behave in certain situations. But behaviour previously attributed to atom statistics is equally likely to arise from cooperative effects.

All microscopic particles can be classified either as bosons (particles such as photons that obey Bose–Einstein statistics) or fermions (particles such as electrons that obey Fermi–Dirac statistics). Although it often takes an elaborate low-temperature experiment to see the difference between bosons and fermions in an atomic system, the distinction is woven into the fabric of the Universe. If electrons were bosons instead of fermions, matter would be different in unimaginable ways, and we would probably not be around to contemplate the issue. For example, the fermionic nature of electrons is responsible for the chemistry of the periodic table. Nonetheless, as two groups from Arizona[1] and MIT[2] argue in *Physical Review Letters*, behaviour that physicists have attributed to atoms being bosons may actually arise from cooperative dynamics between the atoms, and therefore would be equally valid for fermionic atoms.

The case in point is four-wave mixing, a standard tool of nonlinear optics in which two light waves interfere to form a periodic pattern. A third wave diffracted from this pattern generates a fourth wave at a particular frequency. The 1995 achievement of Bose–Einstein condensation — a form of matter in which all the atoms are in the same quantum state — has allowed the development of analogous experiments with atoms[3]. In this case, there are two beams of atoms running at each other. By virtue of quantum mechanics, there is a wave associated with the moving atoms. So the two atomic waves interfere and make a standing-wave pattern — a grating of atoms. A 'probe' atom coming along will act as a wave in its own right and diffract off the grating, resulting in a fourth atomic wave travelling in a particular direction.

The results of experiments on four-wave mixing are usually interpreted as a consequence of boson statistics, specifically the enhancement or amplification of the bosonic atoms or photons. Such behaviour is forbidden by fermion statistics, so other bosonic processes, such as amplification of light or matter waves, would also appear to be ruled out for fermions. But the Arizona[1] and MIT[2] groups show that these processes can indeed occur with fermions. Happily, no violations of atom statistics are required, simply a more mature understanding of how quantum mechanics works.

Consider a more quantitative picture of four-wave mixing with atoms, in which the first two beams, 1 and 2, each have N bosonic atoms with momenta $\mathbf{k}_1$ and $\mathbf{k}_2$. Atom–atom interactions cause an atom to transfer from beam 1 to beam 2, and the conservation of momentum means that the probe atom has to deflect in a new direction, generating the fourth wave. The probability that this process occurs is proportional to the number of atoms, N, available to scatter in beam 1. But Bose–Einstein statistics says that bosons prefer to join already existing bosons, so the probability is also proportional to the number of atoms, N, in beam 2 that receives the probe atom. The resulting N^2 dependence of the probability for the probe atom to scatter in a certain direction can therefore be attributed to bosonic enhancement.

This, though, is not the only conceivable description of four-wave mixing[1,2]. According to quantum mechanics, to find a probability for a transition between two states of a system one first finds a transition amplitude, f, and then takes the square of it. In four-wave mixing there are N transition amplitudes for the scattering of the probe atom from the initial state to the final state, one for each atom that could transfer between the two beams. Another intriguing provision of quantum mechanics states that if in a given experiment it is impossible, even in principle, to distinguish between the paths that lead from the same initial state to the same final state, then the transition amplitudes have to be added. If this holds, then the probability amplitude for four-wave mixing becomes Nf and the probability again scales as N^2. This time, though, the reason is not bosonic enhancement, but another common cause for N^2 dependence in physics: cooperation. Although only one atom was transferred between beams 1 and 2, all the atoms acted in concert to boost the transition amplitude.

The role of atom statistics is therefore only secondary. To date, all the experiments on four-wave mixing[3] and analogous amplification of matter waves[4,5] have been done with bosons because they conveniently provide atom waves that have sharply defined wavelengths. But one might imagine doing the same thing with fermionic atoms. In a Bose–Einstein condensate there is no way to distinguish between the atoms, and cooperation is assured. The defining property of fermions is that only one fermion can occupy one quantum state, so N fermionic atoms cannot be prepared with the same momentum, $\mathbf{k}_1$ or $\mathbf{k}_2$. Still, it is feasible to have atoms with momenta in a narrow enough range around $\mathbf{k}_1$ and $\mathbf{k}_2$ so that the spread cannot be resolved experimentally. Then it is not possible to distinguish between the transition paths, cooperation holds, and the N^2 dependence on the number of atoms emerges. This time, though, the atoms are fermions, and bosonic enhancement is not a viable explanation.

As a classic example of cooperation, imagine a system of N excited atoms. An atom is coupled to the ever-present electromagnetic fields, so an excited atom will spontaneously emit a photon. But if the N atoms reside at equivalent positions relative to the field, they all couple to the electromagnetic fields in the same way and cannot be distinguished by the way they interact with the field. Spontaneous emission from the atoms is then cooperative[6]: the N excited atoms return to their ground state by spontaneously emitting a flash of light whose peak intensity scales as N^2. This dramatic process is called superradiance, but it is a subtle matter of interpretation whether it has been seen experimentally. Superradiance as described by Dicke[6] is one of the key paradigms in optical physics, but an unequivocal demonstration would need the atoms to be placed in a region smaller than the wavelength of the light to fulfill the requirement for 'equivalent field positions'. Even if this were practicable, the interactions between the atoms would spoil cooperation anyway. The moral of this story is that experimental realities tend to obstruct cooperative behaviour.

In my opinion, the main contribution of the Arizona[1] and MIT[2] work is that it demonstrates the fragility of the distinction between atom statistics and cooperative behaviour. Physicists now know that cooperative behaviour may mock Bose–Einstein statistics. Perhaps the converse is true: can Bose–Einstein and Fermi–Dirac statistics be harnessed to assist in cooperative phenomena, such as superradiance? ■

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Neurobiology

Stem cells on the brain

Robert Cassidy and Jonas Frisén

Stem cells have great potential for treating a variety of diseases and seem to hit the headlines almost every week. An extremely pure population of brain stem cells has now been obtained from adult mice.

Many of us were taught in school that we are born with a certain number of nerve cells, which cannot renew themselves. But, after some initial indications in the 1960s, it is now known that our brains are much more capable of change than was previously thought, and that neurons are continuously replenished in some regions of the adult brain[1]. These new neurons are derived from immature cells called stem cells. Stem cells have the potential to generate not only new stem cells but also several types of mature cell; neural stem cells, for example, can produce both neurons and supporting cells called glia. This potential has fuelled hope that brain stem cells might be used in the treatment of, for instance, neurodegenerative disorders such as Parkinson's disease[2]. Yet first we must be able to isolate these cells, and this in turn requires a knowledge of their defining features. On page 736 of this issue[3], Rietze and colleagues

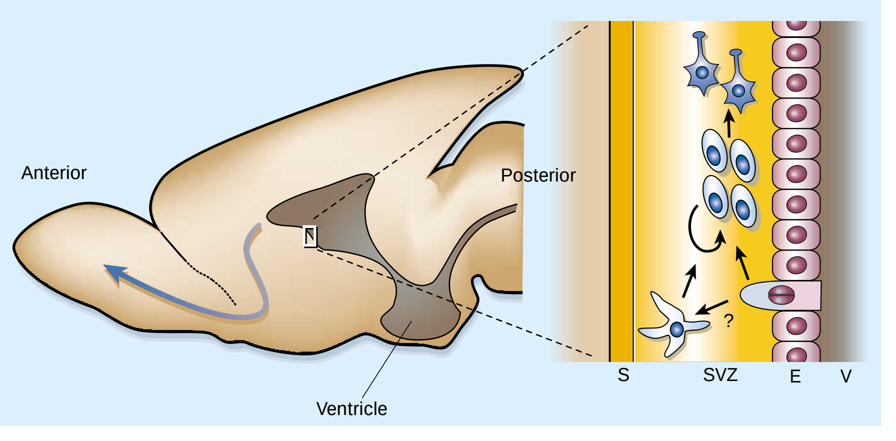

Figure 1 **A source of brain stem cells. Left, a section of the mouse brain (as if it were cut down the midline, from top to bottom), showing the ventricle wall. Inset, details of the ventricle wall. In adult mammalian brains, neurons are born in the subventricular zone (SVZ) between the ependymal layer (E) and the striatum (S) of the anterior lateral ventricle (V), and migrate along the rostral migratory stream to the olfactory bulb (indicated by the long blue arrow in the left-hand part). In this model, stem cells in the ependymal layer generate a population of rapidly dividing 'progenitor' cells (ovals). These in turn generate the newborn neurons (dark cells). Astrocytes (branched cell) could be independent stem cells, or intermediate cells between ependymal stem cells and the progenitor cells.**