Mathematical physics – On the right scent

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NEWS & VIEWS

MATHEMATICAL PHYSICS

On the right scent

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Searching for the source of a smell is hampered by the absence of pervasive local cues that point the searcher in the right direction. A strategy based on maximal information could show the way.

Like many other insects, a female moth releases specific blends of odours — pheromones — to signal her presence to males. The pheromone plume is not a smooth, continuous cloud but consists of intermittent, wind-blown patches of odour separated by wide voids. The probability of encountering one of these patches decays exponentially with distance from their source. Under these circumstances, finding the pheromone source cannot be accomplished simply by 'chemotaxis' — climbing a chemical concentration gradient[1]. On page 406 of this issue[2], Vergassola, Villermaux and Shraiman bring a breath of fresh air to the olfactory search problem: given scanty information, how do moths successfully locate their mates over distances of hundreds of metres?

The problem of searching for odour sources with scarce information is common not only to many air- and water-borne animals[3], but also to olfactory robots designed to search for chemical leaks, drugs and explosives[4] (Fig. 1). Because of the random nature of the odour plume, an exact model of the environment is not available in these cases. Vergassola and colleagues' search scheme[2] circumvents this problem by relying on a probability map of source location that is estimated from the available sensory information — the history of detection and non-detection events.

In an olfactory search, the searcher is initially far from the source and senses small patches of odour. The estimated spatial probability distribution of the source location is consequently flat and broad, and the entropy of the distribution high, reflecting the searcher's uncertainty about the source location. At this stage of a search, making a beeline for locations of maximal estimated probability is a risky strategy. The searcher should instead explore the local environment and gather information so as to obtain a more reliable estimate of the source probability distribution. As the searcher encounters odour particles and accumulates information along its path, the estimated source distribution becomes sharper, and its entropy decreases. Exploitation can now gradually replace exploration, and the searcher can direct itself towards those locations where the probability of finding the source is greatest.

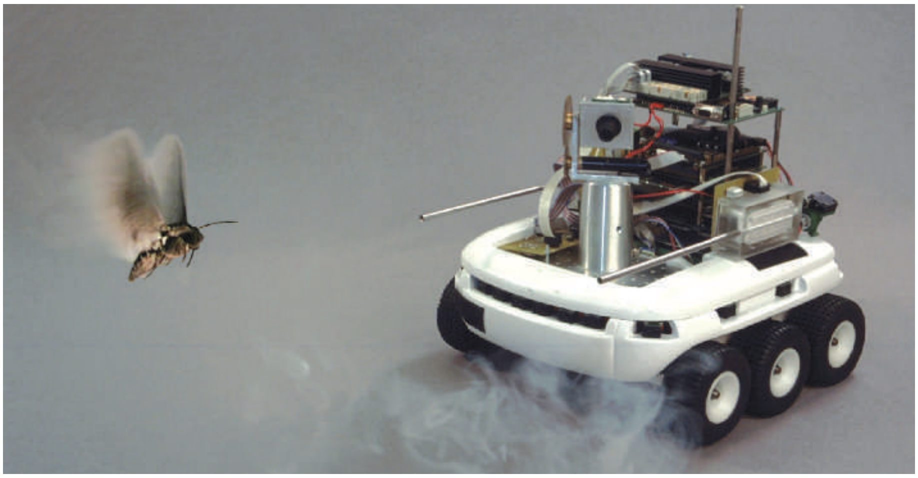

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Figure 1 | Scent trackers. Inspired by the problem of animal navigation in odour plumes, Vergassola *et al.*[2] propose a search algorithm that might help engineers to design efficient olfactory tracking robots.

Striking the right balance between exploration and exploitation is the key to efficient searching when information is hard to come by.

Vergassola *et al.*[2] show that the expected time taken to complete such a search is indeed determined by the entropy of the source distribution. A reduction in the entropy of the estimated distribution is thus a necessary (but not sufficient) condition for an effective search. The authors propose a search algorithm that they term infotaxis. The idea of this algorithm is to take whatever action — making a move or staying still — that maximizes the expected reduction in entropy of the source probability field, and therefore the rate of information acquisition.

Maximizing information gain has been used previously for exploration tasks carried out by autonomous robots[5]. For olfactory searches, Vergassola *et al.* derive a mathematical expression for the variation in entropy that consists of two terms. The first term is identified as exploitative, because it drives the searcher towards points at which there is a high likelihood of finding the source. The second term is explorative, as it favours motion to regions with lower probabilities of source discovery, but high rewards in terms of information useful for improving the estimation of the source distribution. Infotaxis thus naturally combines exploitation and exploration by taking into account both the direct gain specific to finding the source and the knowledge gain from receiving additional olfactory cues. The authors' simulations with modelled and experimental data from turbulent flows indicate that the infotactic search model is significantly faster than explorative or exploitative searches taken in isolation.

The authors note that simulated infotactic paths share qualitative similarities with trajectories observed in the flights of birds and moths. Flights upwind performed by moths attracted by a sexual pheromone have been described extensively at the behavioural level by neuroethologists. When a male moth detects the pheromone of a female, it does not fly straight ahead towards the source, but steers in a zigzag upwind along the pheromone plume. Whenever the moth cannot identify the pheromone plume, it draws wide loops or crosswind turns without forward movement, a tactic known as casting[6]. This odour-modulated behaviour has in the past inspired simple models of olfactory search[7,8]. The striking feature of the infotaxis model is that the casting and zigzagging steps are not preprogrammed by imposing explicit rules of movement such as 'advance upwind' or 'turn crosswind'. Rather, they both emerge naturally from locally maximizing information gain. When navigating in turbulent odour plumes, it seems that the rate of information acquisition could have a similar role to that of the concentration gradient in chemotaxis.

Although the simulated infotactic trajectories resemble their biological counterparts, the control mechanisms underlying the similarities in trajectories might well differ. In moth flights, for example, the temporal regularity of the turns, whether expressed in zigzagging upwind or in casting, suggests the existence of an internal oscillatory mechanism, known as self-steered counterturning[9]. Search models based on counterturning produce trajectories similar to those observed for moths in wind-tunnel experiments[7,8], and might also to some extent account for the complex 'Lévy-flight' patterns characteristic of insect flights in field studies[10].

But Vergassola *et al.* did not develop their search algorithm on the basis of control mechanisms specific to moths. They considered the problem of olfactory search as sufficiently universal that maximizing information gain allows any searcher to track a chemical plume efficiently to its source. This hypothesis is plausible, because many animals, including crabs and birds, exhibit zigzagging trajectories very similar to those of moths, even though these are probably subject to completely different control mechanisms[3]. In infotaxis, crosswind casting and zigzagging upwind can be viewed as parts of a behavioural continuum ranging from pure exploration to pure exploitation.

The authors' work[2] is intriguing in several respects, and will certainly foster future research. Perhaps the most direct implication is the potential use of infotaxis in robotic search applications, in part because computationally efficient algorithms that update a source probability map in real time are already available for on-board implementation[11]. ■

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ATOMIC PHYSICS

The social life of atoms

Maciej Lewenstein

In a trail-blazing experiment 50 years ago, it was observed that photons from far-off stars bunch up. But in fact there's a more general distinction among free, non-interacting particles: bosons bunch, and fermions 'antibunch'.

Counting individual quantum-mechanical objects such as the particles of a complex many-body system — whether photons, electrons, atoms or something else — is an efficient way to learn about the properties of both the system and of the particles being counted. Fifty years ago, Robert Hanbury Brown and Richard Twiss[1] published the results of the paradigmatic experiment of this sort, in which they counted joint detections, in two separate detectors, of photons from distant stars. The two-photon correlations clearly showed that the photons liked to arrive bunched up in groups. Jeltes *et al.*, whose results appear on page 402 of this issue[2], use less well-travelled particles for their investigations — ultracold helium atoms. But they are able, for the first time in the same experiment, to compare and contrast the Hanbury Brown–Twiss (HBT) effect for both 'bosonic' and 'fermionic' particles.

Although the original HBT effect can easily be understood within the framework of classical physics, explaining it in quantum-mechanical terms is more tricky. It requires acknowledging that photons are particles of integer spin, or bosons. These particles are far more gregarious than their fermion (half-integer-spin) cousins, and the bunching phenomenon can be described as the result of constructive interference of the quantum-mechanical probability amplitudes of two (bosonic) photons reaching the detectors. This explanation led Roy Glauber[3] to formulate modern photon-counting theory within the framework of quantum electrodynamics, the quantum field theory of the electromagnetic force. The result was the birth of modern quantum optics, an achievement crowned by a Nobel prize for Glauber in 2005.

Atoms of the helium isotope ^{4}He are also bosons, because they consist of a total of six half-integer-spin particles: four nucleons (two protons and two neutrons) and two orbiting electrons. Experiments with ultracold, metastable ^{4}He have not only famously allowed the observation of Bose–Einstein condensation (the phenomenon of many bosons all adopting the same quantum state), but have also opened the way to precise time-resolved and position-sensitive counting experiments in atomic systems. These helium atoms have a very long lifetime if unperturbed, but can be detected with almost perfect efficiency in micro-channel plate and delay-line detectors.

The first direct observation of the bunching of ^{4}He atoms — the atomic HBT effect — came two years ago[4]. The same authors are part of the team that has now seen[2] the analogous effect in ^{3}He atoms, whose two electrons and three nucleons (only one neutron this time) make them fermions. Fermions obey the Pauli exclusion principle, so unlike bosons they do not like being in the same place at the same time. What Jeltes *et al.*[2] observe in the case of ^{3}He, therefore, is not the bunching characteristic of bosons, but 'antibunching' resulting from the destructive interference of the fermions' probability amplitudes.

The measurement of the HBT effect gives insight into the 'pair-correlation functions', a measure of the probability of finding two atoms at a certain distance apart, and therefore of how an atomic system is put together. Jeltes and colleagues' experiments were performed with dilute, practically non-interacting clouds of atoms in a state of thermal equilibrium. The

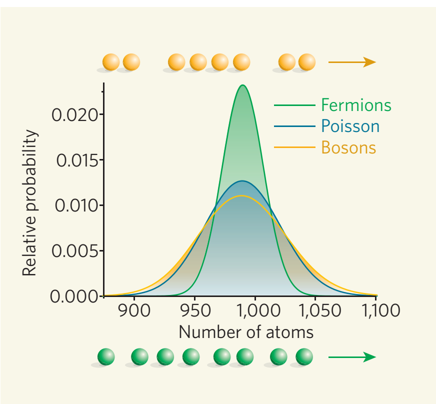

Figure 1 | Bunch, antibunch. Simulated distributions of the number of atoms detected in a certain time-window after 1,000 are released from an atomic trap at low temperature. If the arrival times of the atoms at the detectors were truly random, they would conform to a Poisson distribution (blue). In fact, bosons prefer to bunch, so in the time-window of any one detection event, significantly more or fewer than the mode number can arrive: the counting distribution (yellow) is broader. For fermions, the converse is true: they antibunch, arriving more regularly spaced than purely randomly, and so produce a taller, narrower counting distribution (green). (Figure courtesy S. Braungardt, U. Sen, A. Sen (De) & R. J. Glauber.)