The seventh starling

A flock of starlings wheel overhead, thousands of birds rising, falling, turning as if of one mind. Birds move in flocks; fish in schools; insects in swarms. How do they do it? Can we study them to find quantitative answers or must we simply admire them? **Andrea Cavagna** and **Irene Giardina** do both.

Anyone who has seen the beautiful evolutions of a large flock of starlings swirling and dancing in the sky at dusk can hardly forget the visual impact of such a paradigm of collective animal behaviour. The strongest impression is of the flock as an entity on its own, something more than the mere sum of its individual constituents, the birds. The same impression is prompted by the remarkable coordination of a school of sardines[1]. Yet this collective behaviour stems from some simple rules of interaction between the individuals: stay close to your neighbours (but not *too* close!) and align your velocity to theirs. There is neither a central coordination (a leader), nor any "collective intelligence" but a distributed behaviour, from which coordination emerges[2]. This is the essence of self-organisation.

The concept of self-organisation is not limited to collective animal behaviour, but it is central to disciplines as diverse as physics, economics and robotics. Yet, although we have a complete understanding of the physical laws that lead all spins in a ferromagnet to self-organise and produce a spontaneous magnetisation, we know very little of the mechanisms giving rise to self-organisation in a flock. The basic rules of interaction mentioned above are, in fact, just an educated guess as opposed to a well-established scientific fact. Moreover, they are generic and vague. We can run computer models based on implementation of these rules and check whether these models reproduce patterns *qualitatively* similar to what we observe in nature. In other words, we can get swirling dots on our computer screen that look roughly like a flock of birds—but that is hardly satisfactory science. Until recently we have not had the means to allow direct empirical insight into the laws ruling collective

animal behaviour. What is worse, we could not compare, on a *quantitative* basis, the outcome of numerical models to the natural phenomena they are supposed to describe. We have no way of telling which model best represents what the creatures are actually doing.

The reason for this disappointing situation was the lack of large-scale empirical data. Surprisingly enough, in an era in which splitting the atom into its tiniest parts has become commonplace for science, obtaining empirical data on large groups of animals moving in three dimensions is still a very difficult task.

Obtaining data on large groups of animals moving in three dimensions was until recently impossible.

The difficulty is not due to a technological bottleneck: nowadays, digital imaging and computer power are more than adequate to cope with this problem. The real challenge in getting 3D data, as we shall see, is a statistical and mathematical one.

Recently, the issue of collective animal behaviour has been tackled by a European-Commission-funded project called STARFLAG (*Starlings in Flight*). Scientists from seven European research institutes have focused on the case of starling flocks as a paradigm of collective behaviour. Statistical physicists of the Instituto Nazionale per la Fisica della Materia (INFM-CNR) node, based in Rome, had the task of collecting reliable 3D empirical data on the flocks (see biological systems: flocking at http://www.smc.infm.it).

Starlings (*Sturnus vulgaris*) are abundant in Rome during the winter months. For 3 years the STARFLAG crew spent almost every evening on top of the roof of the Museum of Roman Art—*Palazzo Massimo*—right in the city centre, taking digital pictures of the huge starling flocks gathering there at dusk. Starlings feed in the countryside during the day and come back to the city centre just before sunset. For reasons that are still far from clear, before setting down on the trees for the night starlings spend half an hour performing some beautiful evolutions over their roost. This phenomenon, known as *aerial display*, is convenient for scientists, since they have a predictable site and time of day where one of

the most striking examples of collective animal behaviour can be observed. It must be noted that the site and the time are predictable also for birds of prey. It is by no means unusual in Rome to see a flock contracting, expanding and changing shape while dodging the attack of a peregrine falcon (*Falco peregrinus*). This

was an extra bonus for the STARFLAG scientists.

To obtain the 3D positions of individual birds within a flock, STARFLAG scientists used stereoscopy: when two simultaneous images of the same object are taken from different positions in space, the exact 3D position of that
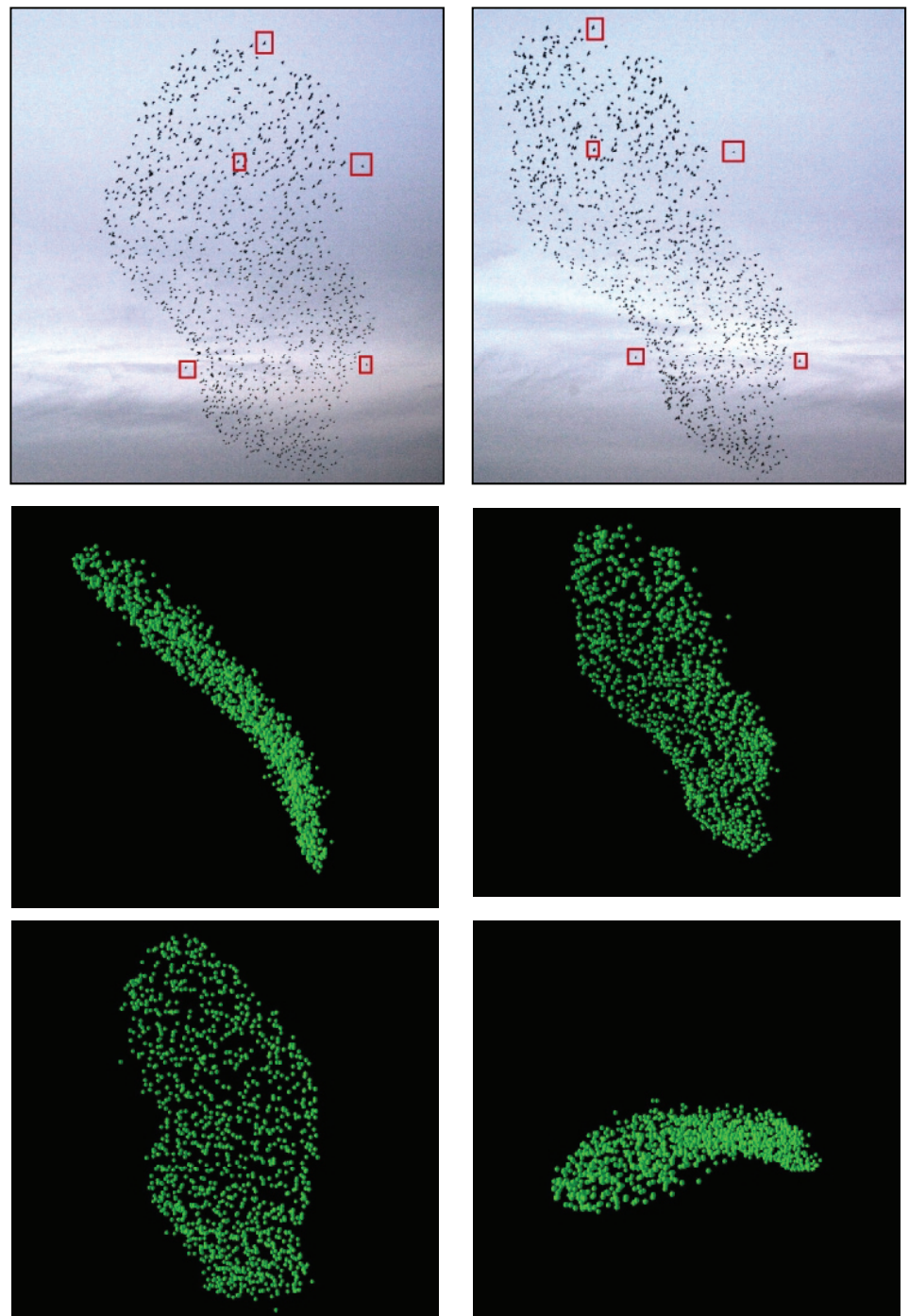

Figure 1. The upper panels represent two photographs taken by a stereoscopic pair of cameras a distance of 25 m apart. The flock is at about 100 m from the cameras. In order to perform the 3D reconstruction we have to match birds on the two photos. In other words, given a bird on the right photo, we must find its corresponding image on the left photo. This is the matching, or correspondence, problem. Due to the long baseline, the mutual positions of birds in the two photographs are radically different. Red boxes indicate corresponding birds. The lower panels represent the 3D reconstruction of the flock from four different perspectives. The striking pancake shape of this flock would be impossible to guess without the 3D reconstruction

object can be calculated. The method is as old as photography itself. Our eyes and brain use it to estimate distances and to provide a 3D perception of a scene in front of us. So, where is the difficulty in getting the data?

To work out the 3D position of a bird (let us call him Jack) we need to measure Jack's 2D position on the left and right photo of the stereoscopic pair. If there are two birds, Jack and Sue, we have to be very careful not to associate Jack's image in the left photo with Sue's image in the right photo, otherwise what we obtain is neither Jack's nor Sue's 3D position, but just a random point in space! As long as we have two birds, it is easy to get the correspondence right. However, when we have *thousands* of birds, the problem of matching each image in the right photo to its corresponding image in the left photo becomes quite severe, as can be seen in Figure 1. Due to the different positions of the left and right cameras—they are 25 metres apart and about 100 metres from the birds—the flock looks very different in the two photos. This is what makes the correspondence, or matching, problem so difficult to solve.

In the past the matching was performed manually: a (very) motivated researcher analysed the two images and decided, case by case, the most likely match. This had to be repeated for hundreds of photos. Apart from the incredible tediousness of such a procedure, it is clear that as soon as the number of animals becomes larger than a few tens, manual matching is out of question. This was the quite mundane reason why, for more than 40 years, empirical studies have been limited to animal numbers in the tens.

The STARFLAG project developed an algorithm able to perform the matching automatically in very large flocks. The algorithm mimics the matching procedure of our brain. When we watch a photo we immediately identify patterns formed by the birds, in the same way that we do for constellations. We then look for similar patterns in the other photo, and in the end we match the birds belonging to corresponding patterns (Figure 2). Similarly, the STARFLAG algorithm matches patterns in order to match birds forming the patterns. However, there is a statistical twist. To each pair of potentially corresponding patterns the algorithm assigns a probability proportional to their geometric similarity. Statistically, a pattern in the right photo has a non-zero probability of corresponding to several patterns in the left photo, and *vice versa*. Among all possible correspondences, the algorithm finds the optimal set, which is the set that maximises the total probability. In this way the matching problem is solved[3].

The human eye tends to select around a dozen stars to "make" a constellation pattern. Our algorithm uses about 30–50 "stars" around each bird to define the pattern. This is why, ultimately, the algorithm is much more powerful than our brain: it can store and process much more information. However, the difference is only a quantitative one. More than 50 stars, or starlings, would cause problems: the extras would be quite far from the centre of the pattern, and their stereo distortion would then also be large. Relative distances are little affected by the stereo distortion as long as they are small!

Once the 3D positions of individual birds are available, we must define the border of the flock. Defining the border is essential for many reasons. For example, we may want to measure the volume of the flock, or its shape. However, the most important reason to identify birds belonging to the border is to get rid of the strong statistical bias they introduce. The best way to explain this crucial point is to discuss a typical (and rather bad) artefact resulting from neglecting border effects.

Consider the distance between a bird and its nearest neighbour—the nearest neighbour distance (NND). The average NND of a flock is an important biological indicator. It is, obviously, the *smallest* value in the set of distances of a bird's neighbours. This means that there is a high probability that a bird belonging to the border has a *larger* NND than inner birds,

A bird's nearest neighbours are found at its side rather than ahead of the bird or behind it.

since, clearly, it has fewer neighbours (a bird on the border has a lot of empty space around!). Therefore, birds on the border bias the average NND of the flock towards a value larger than the theoretical one. However, the number of birds on the border is proportional to the surface area of the flock, while the number of inner birds is proportional to its volume. For larger flocks, the surface-to-volume ratio decreases, and so does the bias of the border. The net result is that the average NND decreases towards an asymptote (the correct value) when N becomes very large.

This argument is purely statistical, and it has no biological content whatsoever. In fact, it is perfectly true for a completely random (Poissonian) arrangement of points. However, if we measure the NND unaware of the statistical bias introduced by the border, we would conclude that, for some strange biological reason, birds in larger flocks prefer to fly more packed than birds in smaller flocks. This is clearly wrong! The only way to get rid of this artefact (and many others) is to eliminate birds belonging to the border from the analysis. Of course, there may be a *bona fide*
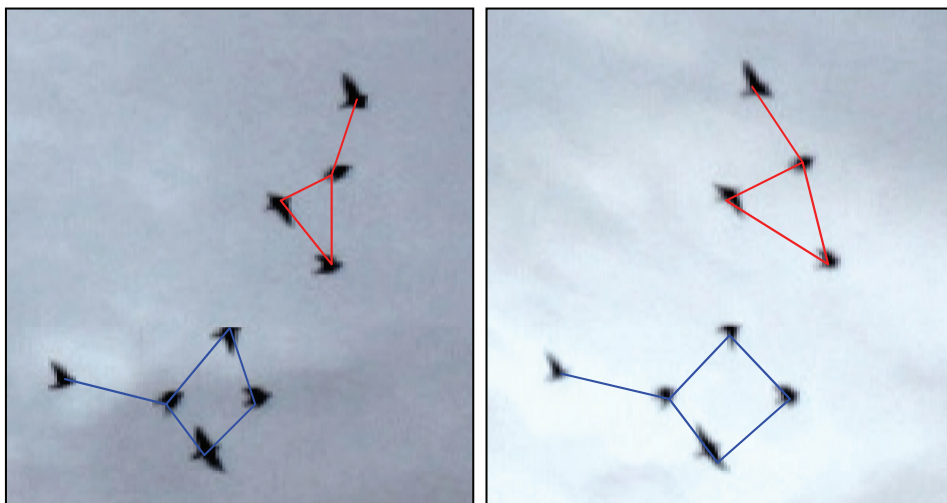

Figure 2. The human brain performs the matching by detecting similar, weakly distorted patterns on the two photos, similar to constellations, and then identifying the vertices of the patterns. The figure shows close-ups of a real flock

biological feature that differentiates border birds from inner birds. They might be weaker, stronger, older, younger, predominantly male, predominantly female, and so on. However, to investigate such possibilities it is essential, first, to eliminate the statistical bias that is present in the trivial random case. To this end defining the border is essential[4].

The STARFLAG project was able to produce, for the first time, the 3D reconstruction of individual birds within flocks of thousands of animals. Such empirical data allowed a direct investigation into the spatial structure of birds within large flocks. The clearest structural feature is that a bird's nearest neighbours are typically found at the bird's sides, rather than ahead or behind the bird, so that the probability that a bird's nearest neighbour is approximately ahead or behind is very low. The reason for this is either the anisotropic visual apparatus of starlings—with eyes on the side of their heads they see better sideways than fore-and-aft—or a sort of "motorway effect", by which birds keep a safe frontal distance to avoid collisions.

The most interesting fact, however, is that this anisotropic structure decays with the distance. The spatial distribution of the nearest neighbour is strongly anisotropic—it will be to one side, not ahead or behind. That of the second-nearest neighbour is a bit less anisotropic, while the spatial distribution of, say, the 10th-nearest neighbour is completely isotropic—it stands an equal chance of being in any direction from our bird. This is because the very interaction between birds, which is the ultimate cause for the anisotropy, decays with the distance, so that the anisotropy decays as well. It is therefore possible to use the anisotropy as a tracer for the interaction between birds, and thus to measure the exact range of the interaction.

The results of this measurement were surprising. All existing models and theories of collective animal behaviour have assumed that each animal interacted with all neighbours within a fixed distance. The STARFLAG data showed something quite different: each bird interacts with a fixed number of neighbours, irrespective of their physical distance. This number is approximately equal to seven. The difference with the assumptions of the models is stark: the data show clearly that the distance within which birds interact is not fixed at all, but rather it depends on the density of the flock. In a packed flock, the seven neighbours you are interacting with are close to you, whereas in a loose, sparse flock they are more distant. Using technical jargon, we may say that birds use a

topological definition of the distance, rather than a standard *metric* definition[5].

This result may seem strange. However, we have many examples of topological distance from everyday life. A classic example is the map of the London underground system. Whenever we take an underground train we do not measure the distance between our starting location and our destination in metres or in kilometres, but rather by the number of stops. Similarly, in a computer network, what matters is not the physical distance between two computers, but the number of intermediate nodes. In both cases we are using the topological distance. While metric distance is the landmark of fundamental interactions in physics, topological distance is more common in social and technological networks. So it is perhaps not surprising to find the same in a socio-biological context such as in bird flocks.

There is, however, a more fundamental reason why starling flocks are ruled by a topological distance. This reason is *predation*. Whenever a flock is under attack it changes shape, density and direction very rapidly. In doing this, the metric distances between birds change drastically. If the flock were ruled by a metric interaction, each bird would be continuously in danger of dropping out of the metric interaction range with the rest of the flock; it would, in effect, "evaporate" from it, and become a single bird, isolated and functioning on its own. A topological interaction, on the other hand, has a strength that is independent of the metric distance between birds and, thus, is significantly more robust when the flock goes through a severe perturbation. Sticking together, keeping the cohesion of the group, is one of the key priorities of the flock, because isolated birds are dramatically more prone to predation than birds within the flock. Not surprisingly, then, evolution has selected an interaction based on the topological distance, which is much more resilient to external attacks. It would be wonderful to collect data on other species to check whether a topological interaction is a general feature of collective animal behaviour.

The final question is, why does each bird keep under control just seven neighbours? The number seven is small considering that the number of birds in visual contact with each individual is significantly larger (around 15–20). So, why seven? There is no definitive answer to this question, but there is an intriguing coincidence. Experiments on birds show[6] that these animals are able to distinguish sets with different numbers of objects, as long as these numbers are below seven. So, they can distin-

guish four from five, but not eight from nine. This coincidence suggests that the number seven may work as a cognitive limit for starlings: they simply cannot keep under control a larger number of neighbours. With the present data it is hard to say whether this is something more that an interesting coincidence. However, the possibility that highly complex cognitive capabilities, such as those involved in numerical estimates, are essential to maintain cohesion of the flock is fascinating. What is certainly true is that the number seven pops up many times, and in many diverse contexts, in biology and in social sciences[7]. Psychologist George Miller even wrote a rather famous paper about "the magical number 7" and its recurrence in the fields of consciousness and memory. Starling flocks provide yet another intriguing case to be added to this list.

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