



Why Animals Swarm for Swarms

Until recently, following the crowd was not seen as a desirable goal in life. These days, however, everyone is talking about swarm intelligence. But are swarms really smarter than individuals? And what rules, if any, do they follow? With the help of new computational techniques, **Iain Couzin** from the **Max Planck Institute for Ornithology** in Radolfzell imposes order on the seeming chaos of swarms.

TEXT **KLAUS WILHELM**

Baboon troops are strictly hierarchical with an alpha male ruling the roost. However, signs of democracy have recently been observed – for example, when the animals are hunting for food. “Even the uninformed animals in the troop participate in decisions about possible food locations and the route the troop will take to find them. This may be advantageous to the dominant male, as it means that he can benefit from the decisions of others when locating good food sources,” explains Couzin, whose department conducts research at the University of Konstanz.

However, upon reaching the food source, the alpha male is the uncon-

tested ruler again, and the other troop members must make do with his leftovers. “Even though individuals are self-interested, it appears that democratic principles still apply,” says Couzin.

FROM CHILDHOOD CURIOSITY TO CUTTING-EDGE RESEARCHER

As a researcher, Couzin’s heart beats faster when he tells stories like this. He comes across like a young boy in the process of discovering the world, but the biologist has been carrying out cutting-edge research for two decades and regularly makes astonishing discoveries. His research passion: the swarm, that most beguiling form of collective.



In nature, migrating locusts form swarms comprising over a billion individuals when too many animals live in one area. Iain Couzin wants to discover what determines the behavior of such swarms. His analyses have shown that the animals are driven by the fear of being eaten.

»» A school of fish is a self-organizing system. Decisions are based on the movements of the individual animals

“The beauty of swarms fascinated me even as a child,” says the 42-year-old Scot. “I always wanted to know why and how animals gather in large groups.”

Today, swarm has become a byword for wisdom. Just 50 years ago, serious scientists fancied that telepathic forces were at work when, for example, thousands of fish move and turn together as if by magic. Even when a swarm spontaneously changes direction, order is maintained and there are seldom collisions. The animals coordinate their movements considerably better than humans driving in traffic.

Birds and insects have similar skills. Consider locusts, for instance. “We fi-

nally have some in the laboratory again!” Couzin’s delight at this is evident. He has had to get by without the insects for a long time – too long for his taste.

HUNTING FOR LOCUSTS IN THE SAHARA

Couzin has many scientific passions, but he is particularly drawn to the behavior of insects – perhaps because locusts have helped him reach some very exciting research findings.

However, he almost paid a very high price for this: when he spent weeks looking for the legendary swarming an-

imals in the Sahara some time ago, he almost died of starvation. “I hallucinated,” he recalls, “and I thought I would die.” In the end, all of the insects were blown away by a sand storm, and Couzin left Africa with no data.

Because of this experience, he focused on researching the insects in the laboratory. With his team, he built a circuit on which the locusts could move as they pleased. Every morning the scientists released up to 120 animals into the perfectly secured circuit. By evening, however, it was found that some locusts had disappeared. “This went on for days and I started to doubt my own sanity, or at least my ability to count.” That was until he was able to examine video recordings of the goings-on in the arena in detail and made a startling discovery: the animals eat one another. After all, locusts are cannibals. Experts had considered them to be vegetarians and cooperative, for example when they suddenly form giant swarms and, as one of the great Biblical plagues, strip entire swaths of land bare.

“But their behavior has nothing to do with cooperation. Rather, they are driven by the fear of being cannibalized by others within the swarm,” explains Couzin. When many insects come together, they can run out of essential nutrients, and that’s when they begin to turn on one another. It was



Couzin (right) and his PhD student Jake Graving observe the swarm behavior of locusts in the laboratory. To this end, they built a circular track from which the animals can't escape.



The fish cellar at the University of Konstanz is lined with aquariums like in a pet shop. The researchers keep predominantly sunbleaks and golden shiners to study what guides the behavior of fish swarms.

found that each individual attempts to eat the one in front of it, and to avoid being eaten by those behind. The result is a mobile cannibalistic horde on a “forced march”.

This discovery was considered nothing short of groundbreaking in expert circles. Couzin and his colleagues found further experimental evidence supporting his theory by severing the nerves in the insects’ abdomens so that they no longer felt the bites from behind. The locusts immediately lost their ability to form a swarm.

With the aid of a computer simulation, Couzin’s team later discovered that the locusts follow the laws of particle physics. The animals are akin to a “flowing magnetic field.” Their bodies align with each other much like small magnets. Changes in the position and orientation of one “particle” can cause neighboring particles to change their

position, too. The individual animals in a swarm synchronize their movements in this way, even over distances of several kilometers.

ANALYSES IN THE WILD, IN THE LAB AND ON THE COMPUTER

This example illustrates Couzin’s unconventional approach to his research – holistic, if you will. He analyzes the animals’ behavior in the wild, in the laboratory and in virtual realities, thus obtaining more comprehensive insights. To do this, he needs biologists, computer scientists, physicists and mathematicians on his team. “We have to teach the computer experts and biologists to speak the same language.” Only by working together can they reconstruct animal swarms on the computer. These computer models trace each individual in a swarm and recon-

struct the animals’ fields of vision. In this way, the scientists aim to decode the rules that govern the swarm.

In addition to locusts, Couzin is also fascinated by another swarm-forming group of organisms: fish. For instance, he studies the golden shiner fish – a native of North America – as juveniles, with a length of around seven centimeters. In daylight, they swim in schools, but they remain motionless when it is dark. The fish follow clear rules when schooling: they seek out the proximity of conspecifics but without colliding with them; a fish on the edge of the school is often the first to react to a stimulus and thus disproportionately influences the movement of the entire group. Furthermore, individual fish tend to adopt the direction selected by a majority. If six fish swim to the left and five to the right, the swarm frequently opts for the left. >



Sunbleaks glide through huge basins. Cameras record their every movement.

With the help of his computer models, Couzin identified three factors that control the behavior of a fish school: attraction, repulsion and alignment of the individuals. For example, if the researchers steer virtual individuals in their simulation slightly in one direction, the group will very likely follow. “So, a school of fish is a self-organizing system. Decisions are based on the movements of the individual animals,” explains Couzin. If individual animals change direction, or suddenly swim more slowly, their neighbors usually react. The sum of the position and direction changes ultimately determines where the school will swim. Furthermore, the process unfolds very quickly and allows individuals to share their “knowledge” with others. The school is therefore more effective as a collective than each of its individual members.

The swarm forms something akin to a collective brain. This enables rapid decision-making and allows many

thousands of organisms to literally meld into a single entity. “Even complex swarm behavior can arise from simple interactions between the individuals. The animals don’t even have to explicitly signal to one another. By responding to the movements of their neighbors, individuals can make highly effective collective decisions,” explains Couzin.

SMALLER GROUPS MAY MAKE BETTER DECISIONS

However, as one of Couzin’s most recent studies suggests, the wisdom of a swarm can diminish if it becomes too big. Sometimes small groups make more prudent decisions. This contradicts the conventional teaching, which takes the view that bigger groups make better decisions. “According to this view, each member of the group makes independent decisions based on the same environmental cues,” says Couzin.

But such conditions are almost impossible to fulfill in reality. Individuals in close proximity within a group tend to have access to similar sensory information, so the cues they experience will not be independent, but correlated. Furthermore, individuals may use multiple cues, or sensory modalities, when making decisions. Using computer simulations of decision-making, Couzin and his colleague Albert Kao were able to demonstrate that the conventional view of the wisdom of crowds does not hold up when this realism is added. In most cases, they found that small to medium-sized groups with between five and 25 members work best. “So the bigger a group gets, the poorer the decisions it seems to make,” says Couzin, summarizing their findings.

But do these laws apply only to egalitarian fish and bird swarms, or do they also apply to animal groups that, like the above-described baboons, exhibit a strong dominance hierarchy? How do

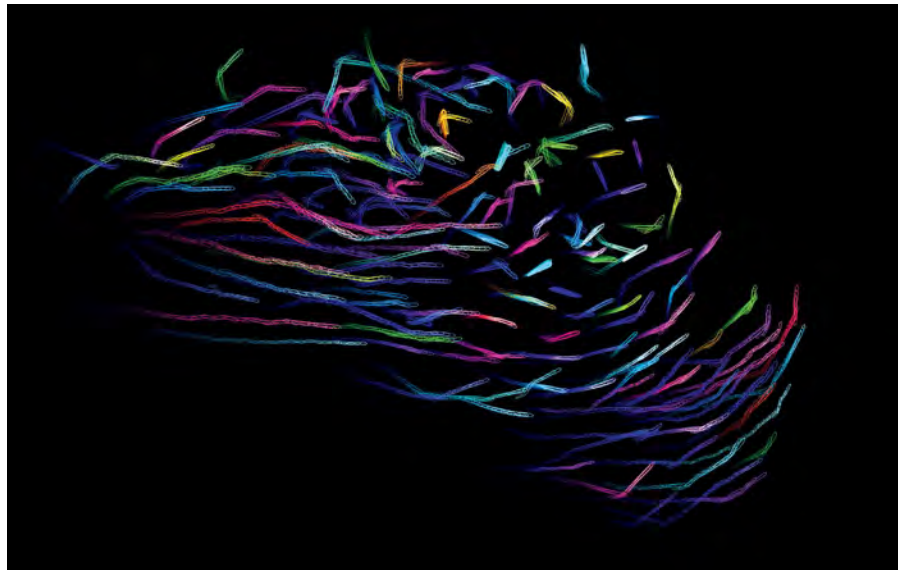
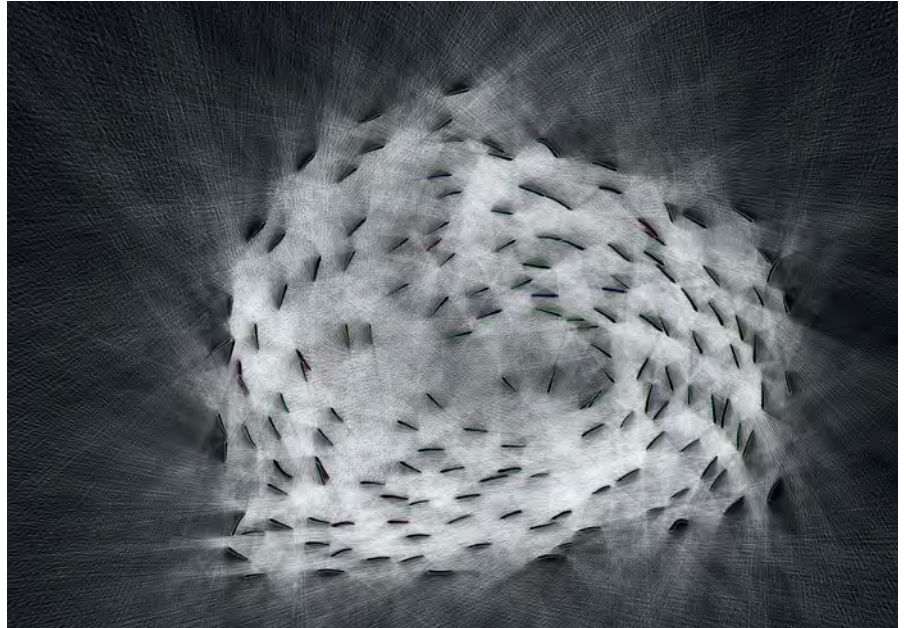
Top Camera image of a swarm of golden shiners in the lab. The fields of vision of the individual fish are highlighted. The greater the overlap between the fields of vision, the brighter they are. The image shows that the fish prefer to stay in positions with the greatest overlap between the fields of vision.

Bottom Swimming movements of golden shiners in a swarm. The colors indicate different individuals.

the animals agree on a direction as they wander through their territory? This is a question that has interested Couzin for years. However, keeping track of the animals when they are on the move is a daunting task. Their movement over rough terrain is simply too swift for researchers to keep up.

When Couzin visited the Max Planck Institute in Radolfzell in 2012, his future colleague Martin Wikelski was able to offer him a solution to this problem. Wikelski develops transmitters with which he can track the movements of a wide variety of species from a distance. For example, the biologist had previously fitted 33 baboons in Kenya with GPS collars. The devices recorded information about the whereabouts of the primates on a second-by-second basis, which Wikelski was then able to evaluate on the computer. Immediately after moving with his research group from Princeton University to Lake Constance, Couzin began to test his models using the data from the wild baboons.

To be able to evaluate the copious GPS data they had accumulated, the scientists created a new software program that accounted for the baboons' movements in real life. In addition, the team observed the animals on site in Kenya. Using the results of their field studies, the researchers were then able to optimize the software, allowing them to determine how the baboons decide on a particular route when they are on the move. "When individual animals move away from the group, the



others have to decide whether to follow them or not. In this way, these animals express their opinion about which route they prefer. If they head off in different directions, undecided members of the group tend to follow the majority," explains Couzin.

Moreover, the route chosen by the dominant animals was found not to in-

fluence the collective decision-making process. Even the alpha male accepts the decision of his entourage and complies with it. The ignorant and undecided group members may have a particularly important role here: "In our computational models, we find that uninformed individuals facilitate and accelerate the process of finding a col-

PEOPLE AS SENSORS

Of all the species Couzin has studied to date, the movements of groups of people have turned out to be the most predictable. His team developed computer vision software for tracking the movements of individual people in large crowds. They record information about where the individuals look and how they behave with each other.

The software is intended to help avoid disasters like the Duisburg Love Parade in 2010. The scientists can use it, for instance, to understand and simulate how crowds of people move in a street. In this way, potential sources of danger during the construction of new buildings and neighborhoods can be avoided from the outset.

In one study, Couzin hired actors and set them the task of behaving in a conspicuous manner on a shopping street and in a large train station. He wanted to find out how passers-by would react to unusual behavior exhibited by individuals. His analyses show that important information can be gleaned from the way people look. People do detect suspicious behavior, perhaps because they consider it to be a potential source of danger. However, they don't usually do anything about it.

Couzin found that observing the gaze of pedestrians allows individuals to be employed as sensors. Furthermore, he found that individuals in crowds follow the gaze of nearby pedestrians. Using a computer program, he and his team were able to analyze these gaze responses, allowing them to detect suspicious behaviors. Such technology could provide useful early-stage indicators of potential hazards even before the people themselves raise the alarm.



The lines of sight of individuals in a crowd of people can be recorded and evaluated using image analysis software. This enables the early identification of conspicuous behavior that may be indicative of potential danger.

lective solution. If, in contrast, many animals have their own ideas about the right route to take, it takes longer for the group to be able to agree on the direction they will all take.”

CHOOSING THE RIGHT ROUTE

But what happens when a stalemate occurs and the different views can't be reconciled? When the same number of animals want to go left and right? Then it depends on the angle between the two preferred options: “If it is smaller than about 90 degrees, the animals following behind opt for the middle path, and in the case of larger angles, they exhibit a strong tendency to select the direction preferred by the bigger subgroup. “That is exactly what we predicted with the model we created for fish,” says Couzin. Hence, like the fish, the baboons also follow a majority-rules principle in their collective decision-making, providing evidence that this is a fundamental principle of swarm behavior across species.

More-recent studies by Couzin and his team have now shown that the baboons also consider their physical environment when deciding which route to take. Using a drone, the researchers took a large number of aerial images of the animals' habitat and, from these, created a high-resolution three-dimensional reconstruction of their habitat. This allowed them to relate baboon movement decisions not only to social factors, but also to the environmental structure. They found that the animals employ roads built by humans, and sometimes also paths beaten by other animals. “This enables them to move faster and more easily between the locations where they feed and sleep,” says Ariana Strandburg-Peshkin, a former doctoral student in Couzin's department. Vegetation, for example, is a considerable obstacle to the animals' movements. Groups slow down in densely vegetated areas, and it is more difficult



Baboons live in hierarchical groups. However, important decisions are not dictated by the group leaders, but are made democratically. If the group members can't agree on the route to be taken, the undecided apes follow the majority – irrespective of the direction chosen by the dominant animals.

able for research on collective behavior. The scientists working there will be able to observe animal swarms in virtual holographic 3-D environments and measure their movements precisely. Specially developed transmitters, sensors and image processing will enable the simultaneous tracking of thousands of individuals in real time.

Five smaller virtual environments where the researchers present real fish schools with a virtual world are already in operation today. Although the fish swim in empty pools, they see virtual rocks, water plants and predators. It will soon be clear whether the fish behave naturally in this environment or not. “It will be unique. Only in Germany would it be possible to build such a research center,” says Couzin. But he still wants to work with locusts again – this time in a more relaxed setting, in the tranquility of Konstanz. ◀

for the baboons to adapt to each other in the directions they take.

A third discovery was that, instead of reacting to the positions of others, baboon motion is more strongly influenced by the routes taken by other baboons within the previous five-minute period – baboons are effectively following in the footsteps of others. “And the greater the number of baboons that cross a certain point in this period, the more attractive it becomes,” explains Strandburg-Peshkin. In this, the baboons somewhat resemble ants, which recognize olfactory traces left by members of their species along their routes. It isn't yet entirely clear whether the baboons also perceive such scents or whether they simply observe and remember the paths taken by their “predecessors.”

Locusts, fish, baboons, ants – Couzin has examined a huge range of organisms in detail and has repeatedly encountered similar laws and rules governing collective life. He is hopeful

that the Center for Visual Computing of Collectives, a major new project he initiated in Konstanz, will uncover far-reaching new insights.

The Center is due to commence operation in three years' time, and will be one of the most modern facilities avail-

TO THE POINT

- The individual animals in a swarm often follow relatively simple rules when responding to others, such as a tendency to be attracted toward, and align direction of travel with, others while maintaining personal space and avoiding collisions.
- The principle of majority rule applies in many animal groups: members normally follow the direction in which the majority of their neighbors are moving.
- Uninformed or unbiased individuals play a profound role in collective decision-making. They allow groups to make faster, and in some cases smarter, decisions.

GLOSSARY

Swarm intelligence: When individuals contribute their skills to a collective, the group can develop characteristics that none of the individuals themselves have. This improves the performance of the group as a whole and can enable it to develop into a kind of superorganism. Examples of swarm intelligence include ant colonies and the internet.