FROM THE NOVEMBER 1997 ISSUE

Quantum Honeybees

How could bees of little brain come up with anything as complex as a dance language?

By Adam Frank|Saturday, November 01, 1997
RELATED TAGS: ANIMAL INTELLIGENCE

Honeybees don't have much in the way of brains. Their inch-long bodies hold at most a few million neurons. Yet with such meager mental machinery honeybees sustain one of the most intricate and explicit languages in the animal kingdom. In the darkness of the hive, bees manage to communicate the precise direction and distance of a newfound food source, and they do it all in the choreography of a dance. Scientists have known of the bee's dance language for more than 70 years, and they have assembled a remarkably complete dictionary of its terms, but one fundamental question has stubbornly remained unanswered: How do they do it? How do these simple animals encode so much detailed information in such a varied language? Honeybees may not have much brain, but they do have a secret.

This secret has vexed Barbara Shipman, a mathematician at the University of Rochester, ever since she was a child. I grew up thinking about bees, she says. My dad worked for the Department of Agriculture as a bee researcher. My brothers and I would stop at his office, and sometimes he would show us the bees. I remember my father telling me about the honeybee's dance when I was about nine years old. And in high school I wrote a paper on the medicinal benefits of honey. Her father kept his books on honeybees on a shelf in her room. I'm not sure why, she says. It may have just been a convenient space. I remember looking at a lot of these books, especially the one by Karl von Frisch.

Von Frisch's Dance Language and Orientation of Bees was some four decades in the making. By the time his papers on the bee dance were collected and published in 1965, there was scarcely an entomologist in the world who hadn't been both intrigued and frustrated by his findings. Intrigued because the phenomenon Von Frisch described was so startlingly complex; frustrated because no one had a clue as to how bees managed the trick. Von Frisch had watched bees dancing on the vertical face of the honeycomb, analyzed the choreographic syntax, and articulated a vocabulary. When a bee finds a source of food, he realized, it returns to the hive and communicates the distance and direction of the food to the other worker bees, called recruits. On the honeycomb, which Von Frisch referred to as the dance floor, the bee performs a waggle dance, which in outline looks something like a coffee bean--two rounded arcs bisected by a central line. The bee starts by making a short straight run, waggling side to side and buzzing as it goes. Then it turns left (or right) and walks in a semicircle back to the starting point. The bee then repeats the short run down the middle, makes a semicircle to the opposite side, and returns once again to the starting point.

It is easy to see why this beautiful and mysterious phenomenon captured Shipman's young and mathematically inclined imagination. The bee's finely tuned choreography is a virtuoso performance of biologic information processing. The central waggling part of the dance is the most important. To convey the direction of a food source, the bee varies the angle the waggling run makes with an imaginary line running straight up and down. One of Von Frisch's most amazing discoveries involves this angle. If you draw a line connecting the beehive and the food source, and another line connecting the hive and the spot on the horizon just beneath the sun, the angle formed by the two lines is the same as the angle of the waggling run to the imaginary vertical line. The bees, it appears, are able to triangulate as well as a civil engineer.

Direction alone is not enough, of course--the bees must also tell their hive mates how far to go to get to the food. The shape or geometry of the dance changes as the distance to the food source changes, Shipman explains. Move a pollen source closer to the hive and the coffee-bean shape of the waggle dance splits down the middle. The dancer will perform two alternating waggling runs symmetric about, but diverging from, the center line. The closer the food source is to the hive, the greater the divergence between the two waggling runs.

If that sounds almost straightforward, what happens next certainly doesn't. Move the food source closer than some critical distance and the dance changes dramatically: the bee stops doing the waggle dance and switches into the round dance. It runs in a small circle, reversing and going in the opposite direction after one or two turns or sometimes after only half a turn. There are a number of variations between species.

Von Frisch's work on the bee dance is impressive, but it is largely descriptive. He never explained why the bees use this peculiar vocabulary and not some other. Nor did he (or could he) explain how small- brained bees manage to encode so much information. The dance of the honeybee is special among animal communication systems, says Shipman. It conveys concise, quantitative information in an abstract, symbolic way. You have to wonder what makes the dance happen. Bees don't have enough intelligence to know what they are doing. How do they know the dance in the first place? Calling it instinct or some other word just substitutes one mystery for another.

Shipman entered college as a biochemistry major and even spent some time working in a biology lab studying the hemolymph--the blood--of honeybee larvae, but she quickly moved her interest in bees to the side. During my freshman year, she says, I became more attracted to the beauty and rigor of mathematics. She switched her major and eventually went on to graduate school and to a professorship at the University of Rochester. For several years it seemed as though she had wandered a long way from her childhood fascination.

Then, taking an unlikely route, she found herself once again confronting the mysteries of bees head-on. While working on her doctoral thesis, on an obscure type of mathematics known only to a small coterie of researchers well-versed in the minutiae of geometry, she stumbled across what just might be the key to the secrets of the bee's dance.

Shipman’s work concerned a set of geometric problems associated with an esoteric mathematical concept known as a flag manifold. In the jargon of mathematics, manifold means space. But don’t let that deceptively simple definition lull you into a false sense of security. Mathematicians have as many kinds of manifolds as a French baker has bread. Some manifolds are flat, some are curved, some are twisted, some wrap back on themselves, some go on forever. The surface of a sphere is a manifold, says Shipman. So is the surface of a bagel--it’s called a torus. The shape of a manifold determines what kinds of objects (curves, figures, surfaces) can live within its confines. Two different types of loops, for example, live in the surface of a torus--one wraps around the outside, the other goes through the middle, and there is no way to transform the first into the second without breaking the loop. In contrast, there is only one type of loop that lives on a sphere.

Mathematicians like to examine different manifolds the way antiques dealers browse through curio shops--always exploring, always looking for unusual characteristics that expand their understanding of numbers or geometry. The difficult part about exploring a manifold, however, is that mathematicians don’t always confine them to the three dimensions of ordinary experience. A manifold can have two dimensions like the surface of a screen, three dimensions like the inside of an empty box, four dimensions like the space-time of our Einsteinian universe, or even ten or a hundred dimensions. The flag manifold (which got its name because some imaginative mathematician thought it had a shape like a flag on a pole) happens to have six dimensions, which means mathematicians can’t visualize all the two-dimensional objects that can live there. That does not mean, though, that they cannot see the objects’ shadows.

One of the more effective tricks for visualizing objects with more than three dimensions is to project or map them onto a space that has fewer dimensions (usually two or three). A topographic map, in which three-dimensional mountains get squashed onto a two-dimensional page, is a type of projection. Likewise, the shadow of your hand on the wall is a two- dimensional projection of your three-dimensional hand.

One day Shipman was busy projecting the six-dimensional residents of the flag manifold onto two dimensions. The particular technique she was using involved first making a two-dimensional outline of the six dimensions of the flag manifold. This is not as strange as it may sound. When you draw a circle, you are in effect making a two-dimensional outline of a three- dimensional sphere. As it turns out, if you make a two-dimensional outline of the six-dimensional flag manifold, you wind up with a hexagon. The bee’s honeycomb, of course, is also made up of hexagons, but that is purely coincidental. However, Shipman soon discovered a more explicit connection. She found a group of objects in the flag manifold that, when projected onto a two-dimensional hexagon, formed curves that reminded her of the bee’s recruitment dance. The more she explored the flag manifold, the more curves she found that precisely matched the ones in the recruitment dance. I wasn’t looking for a connection between bees and the flag manifold, she says. I was just doing my research. The curves were nothing special in themselves, except that the dance patterns kept emerging.

Delving more deeply into the flag manifold, Shipman dredged up a variable, which she called alpha, that allowed her to reproduce the entire bee dance in all its parts and variations. Alpha determines the shape of the curves in the 6-D flag manifold, which means it also controls how those curves look when they are projected onto the 2-D hexagon. Infinitely large values of alpha produce a single line that cuts the hexagon in half. Large values of alpha produce two lines very close together. Decrease alpha and the lines splay out, joined at one end like a V. Continue to decrease alpha further and the lines form a wider and wider V until, at a certain value, they each hit a vertex of the hexagon. Then the curves change suddenly and dramatically. When alpha reaches a critical value, explains Shipman, the projected curves become straight line segments lying along opposing faces of the hexagon.

The smooth divergence of the splayed lines and their abrupt transition to discontinuous segments are critical--they link Shipman's curves to those parts of the recruitment dance that bees emphasize with their waggling and buzzing. Biologists know that only certain parts of the dance convey information, she says. In the waggle dance, it's the diverging waggling runs and not the return loops. In the circle dance it's short straight segments on the sides of the loops. Shipman's mathematics captures both of these characteristics, and the parameter alpha is the key. If different species have different sensitivities to alpha, then they will change from the waggle dances to round dances when the food source is at different distances.

If Shipman is correct, her mathematical description of the recruitment dance would push bee studies to a new level. The discovery of mathematical structure is often the first and critical step in turning what is merely a cacophony of observations into a coherent physical explanation. In the sixteenth century Johannes Kepler joined astronomy's pantheon of greats by demonstrating that planetary orbits follow the simple geometric figure of the ellipse. By articulating the correct geometry traced by the heavenly bodies, Kepler ended two millennia of astronomical speculation as to the configuration of the heavens. Decades after Kepler died, Isaac Newton explained why planets follow elliptical orbits by filling in the all-important physics--gravity. With her flag manifold, Shipman is like a modern-day Kepler, offering, in her words, everything in a single framework. I have found a mathematics that takes all the different forms of the dance and embraces them in a single coherent geometric structure.

Shipman is not, however, content to play Kepler. You can look at this idea and say, 'That's a nice geometric description of the dance, very pretty,' and leave it like that, she says. But there is more to it. When you have a physical phenomenon like the honeybee dance, and it follows a mathematical structure, you have to ask what are the physical laws that are causing it to happen.

At this point Shipman departs from safely grounded scholarship and enters instead the airy realm of speculation. The flag manifold, she notes, in addition to providing mathematicians with pure joy, also happens to be useful to physicists in solving some of the mathematical problems that arise in dealing with quarks, tiny particles that are the building blocks of protons and neutrons. And she does not believe the manifold's presence both in the mathematics of quarks and in the dance of honeybees is a coincidence. Rather she suspects that the bees are somehow sensitive to what's going on in the quantum world of quarks, that quantum mechanics is as important to their perception of the world as sight, sound, and smell.

Say a bee flies around, finds a source of food, and heads straight back to the hive to tell its colleagues. How does it perceive where that food is? What notation can it use to remember? What terms can it use to translate that memory into directions for its fellow bees? One way, the way we big-brained humans would be most comfortable with, would be to use landmarks--fly ten yards toward the big rock, turn left, duck under the boughs of the pine tree, and see the flowers growing near the trunk. Another way, one that seems to be more in line with what bees actually do, would be to use physical characteristics that adequately identify the site, such as variations in Earth's magnetic field or in the polarization of the sun's light.

Researchers have in fact already established that the dance is sensitive to such properties. Experiments have documented, for example, that local variations in Earth's magnetic field alter the angle of the waggling runs. In the past, scientists have attributed this to the presence of magnetite, a magnetically active mineral, in the abdomen of bees. Shipman, however, along with many other researchers, believes there is more to it than little magnets in the bees' cells. But she tends not to have much professional company when she reveals what she thinks is responsible for the bees' response. Ultimately magnetism is described by quantum fields, she says. I think the physics of the bees' bodies, their physiology, must be constructed such that they're sensitive to quantum fields--that is, the bee perceives these fields through quantum mechanical interactions between the fields and the atoms in the membranes of certain cells.

What exactly does it mean to say that the bees interact with quantum fields? A quantum field is a sort of framework within which particles play out their existences. And, rather than assigning an electron to one position in space at one particular time, you instead talk about all the different places the electron could possibly be. You can loosely refer to this collection of all possible locations as a field smeared out across space and time. If you decide to check the electron's position by observing it, the interaction between your measuring device and the field makes the electron appear to be a single coherent object. In this sense, the observer is said to disturb the quantum mechanical nature of the electron.

There is some research to support the view that bees are sensitive to effects that occur only on a quantum-mechanical scale. One study exposed bees to short bursts of a high-intensity magnetic field and concluded that the bees' response could be better explained as a sensitivity to an effect known as nuclear magnetic resonance, or nmr, an acronym commonly associated with a medical imaging technique. nmr occurs when an electromagnetic wave impinges on the nuclei of atoms and flips their orientation. nmr is considered a quantum mechanical effect because it takes place only if each atom absorbs a particular size packet, or quantum, of electromagnetic energy.

This research, however, doesn't address the issue of how bees turn these quantum-mechanical perceptions into an organized dance ritual. Shipman's mathematics does. To process quantum mechanical information and communicate it to others, the bee would not only have to possess equipment sensitive to the quantum-mechanical world; to come up with the appropriate recruitment dance, it would have to perform some kind of calculation similar to what Shipman did with her flag manifold.

Assuming that the typical honeybee is not quite intelligent enough to make the calculations, how does the bee come up with the flag manifold as an organizing principle for its dance? Shipman doesn't claim to have the answer, but she is quick to point out that the flag manifold is common both to the bee dance and to the geometry of quarks. Perhaps, she speculates, bees possess some ability to perceive not only light and magnetism but quarks as well.

The notion that bees can perceive quarks is hard enough for many physicists to swallow, but that's not even the half of it. Physicists have theorized that quarks are constantly popping up in the vacuum of empty space. This is possible because the vacuum is pervaded by something called the zero-point energy field--a quantum field in which on average no particles exist, but which can have local fluctuations that cause quarks to blink in and out of existence. Shipman believes that bees might sense these fleeting quarks, and use them--somehow--to create the complex and peculiar structure of their dance.

Now here's the rub. The flag manifold geometry is an abstraction. It is useful in describing quarks not as the single coherent objects that physicists can measure in the real world but as unobserved quantum fields. Once a physicist tries to detect a quark--by bombarding it with another particle in a high-energy accelerator--the flag manifold geometry is lost. If bees are using quarks as a script for their dance, they must be able to observe the quarks not as single coherent objects but as quantum fields. If Shipman's hunch is correct and bees are able to touch the quantum world of quarks without breaking it, not only would it shake up the field of biology, but physicists would be forced to reinterpret quantum mechanics as well.

Shipman is the first to admit that she is a long way from proving her hypothesis. The mathematics implies that bees are doing something with quarks, she says. I'm not saying they definitely are. I'm just throwing it out as a possibility. And when she publishes her research, probably sometime next year, no doubt many scientists will be turned off by her dragging quarks and quantum mechanics into the picture.

The joining of mathematics and biology is a fascinating endeavor and is just getting under way, says William Faris, a mathematician at the University of Arizona. Connecting quantum mechanics directly to biology is much more speculative. I frankly am skeptical that the bee dance is related to quantum mechanics. The mathematics she uses may be related to a completely different explanation of the bee dance. This is the universality of mathematics. To venture into quantum mechanics may be a distraction.

Shipman isn't the first scientist to go out on a limb trying to link biology to quantum mechanics. Physicist Roger Penrose of Oxford University has postulated that nerve cells have incredibly tiny tubes that serve as quantum mechanical detectors, and other physicists have expressed similar ideas, but they are by no means widely accepted.

It is risky for a young scientist to take on a radical theory. Championing an unproved or unpopular idea is a good way to put your academic career on permanent hold. My thesis adviser was worried, too, says Shipman. He was happy to know that I am beginning collaborations with biologists.

However, Shipman is too excited about the ideas to care about the risk. To make discoveries that cross disciplines, someone has to start. I know there is always resistance to new ideas, especially if you are approaching the problem from a different perspective. Sometimes theory comes before discovery and points the way toward the right questions to ask. I hope this research stimulates other researchers' imaginations.

http://discovermagazine.com/1997/nov/quantumhoneybees1263#.UVrCUTfllBo