3

BEES IN THE LAB

The honeybee is the only one of around a thousand kinds of bees in Europe that has developed an extraordinary form of a differentiated society, with two of its subsystems being storage management and preparation for winter. Unlike, for example, wasps (*Vespinae*) whereby only the well-hidden fertilized queen survives the cold winter and in spring has to build up its retinue from scratch, the honeybees do not depend on a single individual for survival. The strategically reduced population of *Apis mellifera* (the colony is reduced to preserve food stocks) makes it through the winter, and so they are ready in early spring, when it counts, to pollinate our early blossoming fruit species.

With their ability to start work in large numbers in the cool early days of spring, the honeybees have a special status. They fly, if they have to, at outdoor temperatures of 8°C to 10°C (46°F–50°F), though their optimum is between 20°C and 25°C (68°F–77°F). Bumblebees can even fly at temperatures of around freezing point, which gives them a considerable head start in mountainous areas.

Later in the year, bees are only one of many insect groups and at that stage they have to share pollination duties with beetles, butterflies, flies, and a number of other specialists. Although bees are pollinating generalists, meaning that they are not reliant on a few flower species or forms, they are "flower-faithful." If, for example, a bee discovers a blossoming apple tree and has begun to gather the pollen, it will remain there and harvest the resources. It will only change its food source when the present source no longer has enough to offer, irrespective of how tempting or fragrant the other varieties of blossom are. They know the time has arrived when, among other things, it is difficult to unload the nectar that they have gathered on the receiver bees at the hive entrance. The flower-fidelity of the bees is a crucial prerequisite for monofloral honeys to be produced outside of pure monocultures. Bumblebees also learn the respective varieties of blossom, but forage with a strategy that still leads to diversification: Every one of them regularly checks whether it is foraging in the best possible way by occasionally flying to other kinds of blossom.

Each insect has its own particular area of responsibility and deals with very specific plants. Botanists talk of plants that exhibit cantharophily (that is, they are pollinated by beetles), many umbel blossoms, elderberries, privets and herbal shrubs; myophily (pollinated by flies), such as black or white veratrum; and melittophily (pollinated by bees), like most labiates and rosaceae, to which apples and pears belong, as well as blackberries, cherries, plums, and almonds. This division of flora would not continue if the insects failed to recognize the blossoms of their choice and just flew off on haphazard foraging/pollination tours.

Insects can see colors within a certain light spectrum, but they are different from those that humans perceive. So, just as it is difficult for colorblind people to convey what they see to people not suffering from color blindness, we cannot envisage how bees and other insects see color. Our retinas have blue-, green-, and red-sensitive cells. Bees have green, blue, and ultraviolet receptors; red for them is only something dark. Because they can see ultraviolet, bees can see lines, color patterns, and mixtures of colors on some blossoms that we cannot discern. A blossom that looks pure white to us is only white to them if the UV light components are included and the red components are missing; they see yellow blossoms with UV reflection as a bold "bee purple." Their perception of colors is not less pronounced than ours, just different. And our honeybees do react to color signals but, as a rule, do not allow themselves to be lured by the most colorful options.

Strengths like getting off to a good start in the blossom season, which is possible thanks to collective hibernation, their flower-fidelity, and their pronounced color vision would not alone be enough to make bees the proverbially busy gatherers that we know and love. Bees learn particularly quickly and effectively, and optimize their work on the basis of what they have learned. A significant prerequisite for this is their exceptional capacity for navigation.

In order to understand this, Professor Randolf Menzel from Freie Universität, Berlin, has been studying the wings and brains of bees for thirty years. The seventy-two-year-old knows his bees like no one else, and he loves them. Menzel can relate to the godfather of all bee researchers, Karl von Frisch (1886–1982), who is reported to have said that a bee colony is like a magic well—once you have drawn from it and the surface resettles you realize that it is bottomless. This is exactly what Menzel has experienced during his decades of research.

The nature of science lies in dividing marvels into their individual components: How do bees fly? How do they reach their destinations? Which of the very diverse signals do they need to receive and process to navigate successfully?

The flight of honeybees is humdrum and yet fascinating. The bees of a colony, adding together all the individual forays, travel roughly three times around the world for one kilogram (just over two pounds) of honey. One single bee collects a teaspoonful of the coveted sweetener during its stint as gatherer. Cruising speeds of twenty-five kilometers per hour (15 miles per hour), with top speeds even reaching fifty kilometers per hour (thirty-one miles per hour), and up to 280 wing beats per second have been recorded.

How is this possible? The thorax of bees mostly consists of flight muscles. But this alone cannot explain how in a straight flight they can cover a hundred-meter (328-feet) stretch quicker than a world record–holding human sprinter. The comparison with another competitive sport clearly demonstrates this: Even the strongest rowers, irrespective of how much traction per stroke they can generate, could not achieve comparable motions and certainly not the necessary frequency. The power transmission according to the laws of leverage is just not enough.

The propulsion of hymenoptera (bees and wasps), flies, and mosquitoes functions very differently. They do not need two muscles, one pulling up and one down, for every beat of their wings. They use their muscular strength to create a chitin soundboard, the entire middle section of their body vibrating rather like a guitar string. The oscillations are transferred to the wings by an ingenious coupling joint that translates them into movements that are quicker than the human eye can register.

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This ability has caught the attention of bionic researchers, a cross between technicians and scientists, investigating which of nature's inventions are technically adaptable. How can something so small perform to this level with astonishingly little evidence of wear and tear? How exactly does the "patent" of hooks catching a ridge on the lower margins of the front wing allowing the bee to link the fore and rear wings work? The relationship between energy and performance in this efficient use of muscular power is also remarkable. Bees, however, have to refuel intelligently before their forays; they should start with enough energy and carry as little weight as possible so that they can fill their honey stomachs. Additionally, the possibility of an unsuccessful flight has to be taken into account, so they need enough energy to fly back to base.

Possibly even more fascinating than the pure flight mechanics and energy efficiency are the navigational abilities of bees, the question of how bees find their way around, in particular how they find their way to one or more of their food sources, and above all, how they eventually find the way back to the colony safely.

A tiny brain consisting of only about 1 million cells receives, transmits, and switches from one information system to another. How does that work? Does all this function according to a preprogramed automatism? Are they just stimulus-response models, established processes triggered by an appropriate stimulus? No, says Professor Menzel, a rigid program is not possible; bees have to be flexible to a certain extent.

Menzel has systematically researched areas where there are both scope and options that make the bees "competent" to act—particularly their repeated visits to blossoms. He did not have to start from scratch for his studies on the navigation and learning capacities of bees. As early as 1910, Karl von Frisch had demonstrated that bees could learn to recognize a color or a scent if they were rewarded with sugar solution for associations. In the 1950s, one of von Frisch's assistants transferred this food training to individual bees that were kept in tubes so that their behavior in response to a stimulus could be precisely observed—a kind of Pavlov's test for bees. (A reminder: The Russian physiologist Ivan Pavlov conducted an empirical study at the beginning of the twentieth century in which the feeding of his dog was accompanied by the ringing of a bell. After a while the animal reacted to the ringing of a bell by salivating even when food could not be seen or smelled. The phenomenon of classical conditioning had been discovered. A seemingly neutral signal becomes a key stimulus when it is regularly linked to certain conditions.)

Menzel also used these methods for his studies of bees, which he placed in small tubes and stimulated alternately with the scents of geraniums and roses. One of the two scents was rewarded with sugar solution, which led to an extended proboscis for this scent, even when subsequently there was no longer a reward. Menzel opened the head plate of the bees and took photographs with a special camera so that he and his team could monitor and localize the processes in the bee's brain during the cognition and learning of the conditioning of a scent. Using florescent dyes, they were able to display which brain cells were activated by scents and in which area of the brain this was taking place: red signaled particularly high activity, and blue inactive nerve cells. Having been fed exclusively in association with the scent of geraniums, the test bees only reacted to these smells. Presented with the scent of roses, certainly still appetizing but which had proven to be disappointing, they remained passive.

From the Pavlovian bee test it can be deduced that bees are not solely preprogrammed creatures. Their reflexes can adapt to individual experiences.

Those wanting to see Menzel at work outside his lab have to travel in summer to Klein Lüben in Brandenburg where he has set up a kind of open-air test track for bees. The landscape is not exactly what you would expect to find in tourist brochures; it's a little bleak and short on distinguishing features. However, this is just what the scientist wants and it suits his purposes perfectly. He wants to make and remove the features himself to measure the effect on his flying test objects. It would have been more difficult to say what the individual bees were reacting to had there been other competing landscape features. On top of this, Menzel chooses a time when there are few other blossoms on offer so that his flyers can totally concentrate on his test feeding points. The open landscape, which allows for trouble-free trial conditions, was not the only piece of luck for the bee researcher—telemetric technology has made significant progress in recent years and his experiments also profit from these advances. In the 1960s, scientists started attaching bulky transmitters to larger animals, such as red deer or bears, using the signal to track and record their migration routes. In this way, wildlife biologists using even more cumbersome antennae discovered how red deer use their territory both daily and throughout the year: where they eat, where they sleep, or how quickly they settle down after being disturbed. The first birds that were strong enough to carry the smaller version of the transmitter in flight were wood grouse, cranes, storks, and swans. Thanks to these pioneers of telemetry, ornithologists were able to gain new insights into flight paths, winter habitats, and traveling speeds.

Recently it has even become possible to fit insects with antennae so that they can be tracked by a special radar unit. Menzel's bee antennae weigh twenty milligrams (a fraction of an ounce), and at twelve millimeters (a fraction of an inch) are considerably taller than the bee itself. Although a bee only weighs between eighty and hundred milligrams, the weight of the thin wires is, according to Menzel, relatively unproblematic—bees carry up to sixty milligrams of nectar and pollen to their hives per foray. The weather conditions are critical, though: the test bees cannot fly at wind speeds beyond thirty to thirty-five kilometers per hour (18–22 miles per hour). Two to three hours' flying time and a total of up to forty kilometers (twenty-five miles) is standard for the test bees, with the altitude varying between one and ten meters (three to thirty-two feet) above ground level.

When Menzel began his experiments on bee navigation, he already knew a considerable amount about its hows and whys. Bees are flying data gathers and processors. It was recognized that bees had special senses at their disposal, and that there was a certain hierarchy of the sensory impressions: Optical information is the key; route markers, color signals, and structures are pieced together, making and updating a "map" in the bee's brain where they can be accessed when required. They create, as it were, a matrix into which other information can be slotted.

An important tool in this process is the sun as compass. Although the point of orientation on which this compass is aligned changes its position during the day, the bees can recognize directions. And they can use this complex navigational instrument even when it is almost totally overcast. A small window of clear blue sky, no matter where, is all they need to determine the position of the invisible sun. Depending on the height our central star has just reached, typical patterns of diffused light appear in the upper atmosphere, appearing in the sky like wallpaper moving with the sun which can only be seen by those with ultraviolet vision.

The bee's eyes can do a great deal more to make life at breakneck speeds possible. They enable bees to estimate distances from the movement patterns that appear on the structure of the ground beneath them. On top of this, insects must quickly recognize movement, as it could be coming from a rapidly approaching predator. Their compound eyes can do this much more effectively than camera-type eyes, which humans have, can. Whereas humans can only differentiate a few individual images per second, bees can register 265 images. For our eyes, a walking pace of sixteen images per second just gives us the perception of general motion. A bee would see at more than two hundred images per second a series of jerky individual images. This is why they identify a quick and hectic defense as movement and thus a threat. This is also why it is better and safer to repel them with slow tai chi–like movements than with rapid swatting. Dragonflies, the fastest and most acrobatic fliers of the insect world, process motion information of well over three hundred individual images per second and are even more visually refined than bees or wasps.

The compound eyes of insects, enabling almost all-round visibility, consist of many separate single lenses—ommatidia—on a bulging spherical or oval surface. A single lens in the lower area of the eye's curvature can recognize a rapidly approaching flying object coming from below. A split second later, the flying object enters the field of vision of another ommatidium further up on the curvature. The time lag between the two warnings arriving at the insect's brain is used to calculate the speed of the approaching object—similar to the operating principles of the old-fashioned speed traps where the speed of a vehicle can be calculated by using the time taken between two fixed points.

Much has been written about the compound eyes of insects, but little about the olfactory organ of bees. Using their "noses"—tiny pores on their feelers covered by delicate membranes—bees can, unlike us, accurately smell in stereo. They recognize and distinguish scents and the direction from which they are coming—a particularly useful aptitude for close orientation, especially as the insects' eyes, being receptive to motion information, can barely recognize the shapes of flowers and blossoms from a distance of one meter (three feet). Visual flight for bees is also always a "nasal" flight.

On top of their highly sensitive optical and olfactory senses, bees have a couple of other special abilities. A sense of electric fields enables them to reliably reach their destinations. The Johnson's organ on their antennae—a similar structural principle to that of air pressure gauges in aircraft—measures the oncoming air and conveys to the brain when and how flight attitude or the number of wing beats need to be adjusted.

Bees can also detect the Earth's magnetic field, although exactly how they do this remains unclear. Two theories are that it is down to magnetic crystals in their abdomens or that it is simply another special feature of their compound eyes. At the moment we know very little about what the honeybees use their sense of magnetism for. The orientation of the honeycombs is clearly determined by magnetism and the waggle dance is also thought to be influenced by magnetic fields. Whether and how it is incorporated in navigation remains unanswered.

When a bee's brain is functioning without any disturbances, the navigational systems can be changed according to the situation, rather like the captain of a ship putting aside his telescope in sea fog and switching on the radar. Having this option is crucial; if bees were only out and about in optimal, clear flying conditions they would not be the best pollinators in the world—and we know that they are.

The most remarkable form of communicating information—the famous waggle dance—had already been observed by 1828 by a German beekeeper named Nikolaus Unhoch: “It may seem ridiculous to some, maybe even unbelievable, when I claim that bees also [...] enjoy a certain revelry and pleasure amongst themselves, so much so that according to their nature they engage in a special dance. [...] What this dance actually means, I cannot yet explain, whether it is a bold gleefulness or encouragement [...] will have to be settled in the future.”[1]

Unearthing the meaning of the dance took almost a century. At the beginning of the 1920s, Nobel Prize winner Karl von Frisch meticulously researched and described the significance of the dance. He discovered that the returning nectar foragers that had found a good source of food broadcast it by doing the characteristic circular dance, which could be translated as “Look! I’ve got some good news!” They interrupt their rondo every now and then to share out tasters from their source. Once interest has been aroused, they disclose, by means of a precisely choreographed waggle dance, where the nectar can be found.

By wiggling its abdomen, a bee communicates pointers about the direction, distance, and quality of the food source; the directional information of the dancing bees refers to the angle between the sun and the food source. If, for example, the objective is a tempting cherry tree in full blossom east of the hive, the bee’s tail will point vertically when the sun is in the east. About three hours later, when the sun is in the southeast and the cherry tree is to the left of the sun, the tail position would then alter to forty-five degrees. The distance is communicated by the duration of waggle runs that are carried out in semicircles.[2] The more vigorous the waggle the more worthwhile the food source. The amplitude of the acoustic and sensory signals during the waggle dance might be passing on further pieces of information that go beyond the parameters of distance, direction, and delectability, but we can’t be sure. There is much that we do not know yet about the many details that are hidden in the dance information and which are probably directed to sensory channels that we are not yet aware of. We are certain, however, that inside the hive an important role is played by a kind of hearing with feelers. Bees in the vicinity follow the movements and sounds of the waggle dancer very closely and can then fly off to the specified destination. Should they also find the source rewarding, on returning to the hive they dance the corresponding dance. So, a bee subsequently turns something that was passed in complete darkness into directional accuracy in the open air and light. It is able to translate directional indicators that were passed on to it vertically (in the perpendicular honeycombs) into a horizontal landscape outside. That requires a simple form of abstraction abilities.

In order to learn more about the famous sun compass of the bees, Randolf Menzel and John Cheeseman, from the University of Auckland, did something that all scientists like to do when they want to understand how something usually works: they interfered with the usual process. Using isoflurane, they anesthetized bees that were returning to the hive from a good source of nectar. On waking up and trying to fly back to that food source, the bees began by flying off in the wrong direction—but according to their former information it was the right direction. Something in their brains "knows" that the position of the sun shifts clockwise some fifteen degrees per hour. The test bees behaved correspondingly, but as if there had not been any movement in the sun during their anesthetized phase. The isoflurane had stopped their internal clocks.

"Bees can memorize navigation, that much is clear," says Menzel, smiling, "but that is only a rough description. Is it only—and I deliberately say 'only'—a route that they themselves have in their heads? When they fly back to their hives from a fully laden cherry tree are they just rewinding the tape of the route they have already flown?"

An experiment proved particularly revealing in the search for answers: Menzel and his team set it up so that a marked bee fitted with a transmitter—let's call this bee Red 23—was witness to a waggle dance. This meant that Red 23 was in the immediate proximity of a sister-bee that was communicating information about the distance and direction of a particularly good food source in a bee-like manner. Red 23 had previously foraged from an excellent source which was in the meantime running dry. This was why it had returned to the hive and observed the dance of other bees.

Where would Red 23 fly to next? Could it trust the information passed on by the dance, even give it precedence over its own knowledge? Red 23 “decided” to return to its own tried and tested food source. In the meantime, Menzel’s students had cleared away the food source without a trace. A little later, the team eagerly followed Red 23’s transmitted signals on a monitor. Clearly irritated and indecisive, the bee circled for a while above the site which, on the basis of its earlier memories of a successful foraging flight, it had quickly and correctly refound and which again had proven disappointing.

It was now expected that Red 23 would either fly back to the hive to gather new instructions or set off independently on a search for another, completely new food source. It did neither one nor the other. It flew directly to the site pointed out by the waggle dance shortly before its departure. The information received from the waggle dance that it had not used was not only available later but would let it take the direct route to the new site although it had only been described to Red 23 in relation to the hive.

This meant that it used information about the terrain itself and not from the flight there. What makes this remarkable, to put it in human terms, is that it either must have carried some form of “calculation” or could access a memory somehow resembling an inner map of the landscape. The “calculation” could only have been made if the bee took into account both the paths—from the hive to the food source and from the hive to the site indicated by the waggle dance—relating them in such a way as to determine the direct path between the two sites. In mathematical terms, this is vector integration. Such calculations are comparable to trigonometric operations used in surveying.

But maybe bees have a completely different procedure at their disposal? Namely, a concept of landscape in the form of an inner map. Using this, bees could successfully travel by the most direct route from any site in their memories to another.

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What is the upshot of the experiment with Red 23? Red 23 behaved in a way that leaves an observant person with little choice other than to assume some kind of decision-making process: "No, I'm not going to go to the source that that bee's waggling about; I'm off to my tried and trusted site." And immediately afterward, Red 23 "revisited" that "decision," performing an unarguably unusual navigational feat by flying to a site as if it were using an inner map. How this is structured remains a puzzle.

All things considered, it is legitimate to ask whether creatures with brains the size of pinheads "plan" their actions with the aid of map-like memories. But what could be meant by "planning" for insects?

That insects have a certain kind of scope for decision making or a spatial power of imagination stretches the bounds of human imagination. Menzel stiffens a bit, and now has to choose his words carefully. Terms like "imagination" could encourage the research competition to criticize him for trying to "humanize" bees, in Menzel's field a damaging slur on reputation of the highest order. "What we do know and can say is that bees have a memory, that they use this memory to navigate and by doing so can factor in their own experiences and information that they have gathered from their base. And that they can make decisions."

Now that he has uttered the magic words, Menzel clarifies: "When we say that they make decisions between various options, we mean natural processes in bees' brains which have nothing to do with what we would call human, considered knowledge. Cognitive psychologists speak of implicit knowledge, knowledge that is automatically at our disposal." But knowledge can take many forms, and we can say that bees have moments of decision, certain degrees of latitude—will one or the other flight plan be adopted or even none of the already known routes? If one such decision later proves to be unproductive, earlier knowledge that had not been previously used can still be deployed, it is still available. It is not knowledge as we define it in everyday life but what Menzel calls a kind of "bee knowledge," to differentiate it from other forms of knowledge.

If individual bees have such latitude in making decisions then it raises the question of individuality in the swarm. Menzel thinks for a long time. He does not want to make any defining statements about it, but he has observed in the course of his food training experiments that not all the test subjects behave in the same way, that within the social fabric of a colony in which conformity plays a pivotal role there is no such thing as total conformity. He points at an array of scent tubes: "Look at this! When I've trained thirty or forty bees then I know that that one scrabbling around is Blue 59; it always moves in a slightly different way to the others."

US colleagues of the Berlin bee neurologist express themselves more emphatically: "Our results say that novelty-seeking in humans and other vertebrates has parallels in an insect,"[3] said Gene Robinson, an entomology professor from the University of Illinois.

Robinson's team concluded that scouting bees, which scout out new sites for the colony, are especially brave or adventurous. As soon as a swarm has settled somewhere temporarily after having left its original quarters, scouting bees survey the vicinity, usually in bands of around a hundred individuals. The scouting bees also prove to be more active and successful than the majority of their sister-bees in the day-to-day bee activities, like discovering and communicating food sources.

The research team compared the brain activities of the "brave" scouting bees and the comparatively unremarkable remaining bees. "The magnitude of the differences was surprising given that both scouts and non-scouts are foragers," the Illinois team summarized.

Recruits in the field, and experienced foragers whose hive has been moved, explore the surroundings in an orientation flight, not yet interested in foraging for nectar and pollen. They make large loops around the hive, creating a kind of memory of the landscape, slowly increasing the scope, first nearby and then further afield. These exploratory flights are essential for survival. The bees' accuracy in finding the "right" blossoms is not a crucial factor, but it is essential that they know the environs and can find their way back to the hive. A mistaken flight to an alien colony could prove lethal—the guard bees there would make short work of any foreigners emitting the wrong signals. In addition to making orientation loops, before leaving a food source the foragers make a reconnaissance of its surroundings. They memorize colors and shapes, thus making their next visit easier.

Martin Giurfa and Aurore Avarguès-Weber from Toulouse University are also interested in the apparent contradiction that primitive insect brains could have learning capacities. They put forward a working hypothesis that bees can not only recognize and remember a pattern but that they can also find it even if, to a certain extent, it deviates from what they have learned. Using sugar solution as a reward, they trained bees not only to differentiate simple dot-and-dash face-like representations from other patterns of dots and dashes but also to prefer them. After a short time, the test bees flew confidently and reliably to the sketched faces. This also worked when the faces were hidden in complicated patterns and even when they were embedded in enlarged passport photos. However, bees, unlike humans and many other higher animals, cannot distinguish individual faces. The dot-and-dash diagrams that the bees recognized could possibly be the equivalent of an idiosyncratic kind of blossom that they have recognized and memorized before they fly to it and harvest it.

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Experienced foragers are more successful than recruits; in the course of their lives they have gathered not only honey but also information. This is possibly also the reason for the brain growth that has been ascertained. Experience stimulates stronger links between the nerve cells in certain areas of the brain that are particularly important for memory formation and thus increase the volume of the brain.

Menzel describes this process—the storing of information in the memory—in a characteristically scientific way as "alterations to the circuitry of the nerve cells." Yet in addition to all the definitions and dissections, the weights and measurements, and all the objective analyses, he adds, "You can make hypotheses, you can verify them or reject them but if the bee wasn't such a wonderful work of art, my urge to research wouldn't have got me too far. You have to love them both as individuals and as a social community."

Evolutionary biologists go into raptures when talking about bee family units. They regard a bee colony as an entire organism, like a highly structured body with many cells and organs. And the organs in this superorganism, to stick with our image, can change their functions. In the course of their lives, bees perform a variety of very different tasks.

A newly hatched bee, in the warm half of the year, begins its roughly five-week-long life as a cell cleaner; it cleans the brood cells that its younger sister-bees have just left. It only holds this job for one to two days. From the third until the twelfth day of its life it is a nurse bee, meaning that it feeds the larvae. For the first three days of life the larvae receive royal jelly, a juice produced in its salivary glands; then they receive normal rations of nectar and pollen. The queen is the only bee to be fed lifelong supplies of royal jelly—hence its name.

While the majority of bees hold a number of jobs during their lives, a few specialist courtiers remain to feed the queen. When the queen is fed, it secretes a substance that attracts these courtiers and ensures that they continue to do their jobs as royal providers. For the majority of bees, however, after a short time as cleaners and nurses there follows a period when they take on three special jobs one after the other.

First, they become specialists in processing the reserves of nectar; the foraging bees deliver it, the current crop of specialist bees chew it, and then fill and seal the cells. Simultaneously or subsequently, they qualify as honeycomb builders, also producing the building materials. The honeycomb is made from wax which they excrete from special glands on their abdomens. Wax is an incredible substance, consisting of around two hundred different compounds of saturated and unsaturated hydrocarbons, acids, and esters, to name but three components. Later, in their third development stage, they become guard bees at the entrance to the hive. Only those bees with the right family "smells" are granted entrance; every now and then, foreign drones that have strayed after a nuptial flight are also allowed in.

Only after twenty days—after they have hatched into bees, after they have been cleaner and nurse bees, and, according to the needs of the colony, after they have completed the three stages of training—do the honeybees fly off as foragers to deliver nectar, pollen, and water to the hive.

Water is transported to the hive in their honey stomachs, mainly to control the temperature in the hive, as it evaporates through a collective buzzing of wings protecting the sensitive brood from overheating. Within the hive a constant temperature of 35°C (95°F) has to be maintained, and only in the winter can the temperatures drop below 30°C (86°F). If heating is necessary, the bees decouple their wings so that their muscles run at full power without moving their wings.

In addition to the normal career sequence from nurse to load carrier, there is one more temporary, special development. In early fall, a certain generation of bees can considerably extend its normal five-week lifespan. These winter bees, as they are known, survive the winter by keeping the queen warm and feeding it, and can live in the hive for up to five months. Science is still seeking the mechanism that allows the organisms of bees to switch from a short lifespan to longevity at the end of the reproduction season. One hypothesis suggests that in fall the workers feed each other with royal jelly, the energizer that allows the queen to live so long. The theory is that as the production of eggs slows to a standstill with the onset of winter, royal jelly is no longer needed in the same quantities for feeding the queen and the larvae. This switch to longevity, albeit gradual, is still not completely understood.

The capabilities and endurance of bees is impressive, but possibly even more fascinating is the interplay. The question of what governs this is not only interesting to zoologists. For a number of years scientists have been focusing on social insects, and there have been increasing attempts at distilling the entirety of bee or ant colonies as conceptual models for human coexistence. "Global society can be seen as an autopoietic network of self-producing components, and therefore as a living system or superorganism." So said the Belgian star of theoretical cybernetics Francis Heylighen, who also coined the term "collective intelligence."[4] As with all biological processes, such superorganisms develop in the course of evolution and we are gradually beginning to understand more. Technologically, according to the principles of optimization, there have already been tangible results—the building of small robots, emulating the principles of swarms. Technicians have already succeeded in building small helicopters that can swarm like a flock of starlings without crashing into each other and artificial beetles that can overcome obstacles by linking together to form a bridge. And there are already drones that can fly in swarms, named after their archetypes in nature and made airworthy by funds from the US military budget.

Humans would not be humans if at this point they did not think ahead. Could we not make ourselves independent of bees? Is it unimaginable that pollination could be carried out by robot bees that can exchange information as the bees do? Opinions are divided as to whether this vision of the world, in which small, automated bees buzz around instead of the originals, is a scenario of hope or of horror.