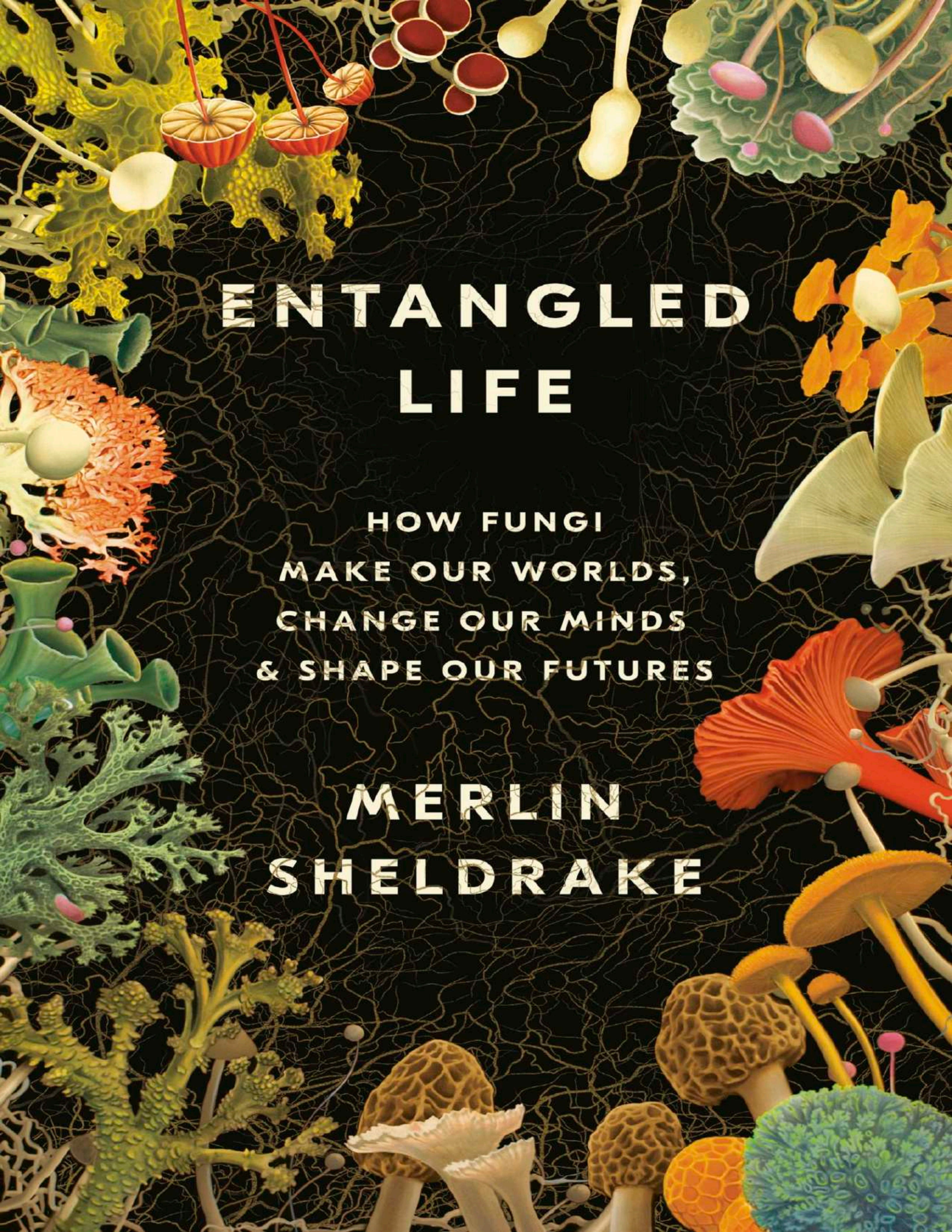

ENTANGLED LIFE

HOW FUNGI MAKE OUR WORLDS, CHANGE OUR MINDS & SHAPE OUR FUTURES

MERLIN SHELDRAKE

MORE PRAISE FOR **ENTANGLED LIFE**

"A delightfully granular debut…From bread to booze to the very fiber of life, the world turns on fungus, and [Merlin] Sheldrake provides a top-notch portrait."

—*Kirkus Reviews* (starred review)

"A revelatory look at fungi that proves their relevance to humans goes far beyond their uses in cooking…[*Entangled Life* is] a thoroughly enjoyable paean to a wholly different kingdom of life."

—*Publishers Weekly*

"*Entangled Life* is a triumph and a thing of vast beauty."

—TOM HODGKINSON, author of *The Idler*

"I was completely unprepared for Sheldrake's book. It rolled over me like a tsunami, leaving the landscape rearranged but all the more beautiful."

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"*Entangled Life* is a revelation. It is a radical, hopeful, and important book and I couldn't put it down. With elegance, wit, and clarity, Sheldrake engages us in the hidden world of fungi, a miraculous web of connections, interactions, and communication that changes the way we need to look at life, the planet, and ourselves."

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"Sheldrake awakens the reader to a shape-shifting, mind-altering, animate world that not only surrounds us but intimately involves us as well. A joyful exploration of the most overlooked and enigmatic kingdom of life, and one that expanded my appreciation of what it means to be alive."

—PETER BRANNEN, author of *The Ends of the World*

"It is impossible to put this book down. *Entangled Life* provides a window into the mind-boggling biology and fascinating cultures surrounding fungal life. Much like a mycelial network, the book's tendrils extend into the deepest reaches of fungi's incredible properties, their histories, as well as their innumerable uses in materials, medicine, and ecology. Sheldrake asks us to consider a life-form that is radically alien to ours, yet vibrant and lively underfoot."

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"*Entangled Life* is an adventurous and indeed daring book, opening several unfamiliar micro-domains in the organic life world and its multiple connections. There is much to be learned in this wide field, and this vivid, scrupulous guide points the way!"

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"Unputdownable, this extraordinary work explores the awesome range of activities of fungi: enabling the first life on land; interacting in countless ways with other life-forms; shaping human history and potentially safeguarding our future. At once rigorously scientific and boldly imaginative, *Entangled Life* raises fundamental questions about the many natures of life on Earth."

—NICK JARDINE, emeritus professor of history and philosophy of science, University of Cambridge

"*Entangled Life* is a remarkable piece of work from Merlin Sheldrake that manages to be at once scholarly and visionary and yet remains a deeply engaging and enjoyable read. This book provides a new and penetrating analysis of the fungal kingdom of life that will be a greatly enriching read for all students of the living world."

—DR. IAN HENDERSON, lecturer in plant sciences, University of Cambridge

"In his remarkable first book, Sheldrake takes us on a host of profoundly eye-opening journeys into the astonishing world of fungi. After reading Sheldrake's masterpiece, I am more convinced than ever that we will never solve the grave problems of our times unless we deeply re-entangle our lives 'fungus-style' into the living fabric of our lustrous planet."

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"Fungi are fascinating! Elegant life strategies meet with delicate omnipresence, driving global ecosystems. Sheldrake's book informs and offers new concepts. Looking through Sheldrake's lens, fungal biology integrates with art, philosophy, and human society. His voice is real and personal. His book educates and entertains."

—UTA PASZKOWSKI, professor of plant molecular genetics, University of Cambridge

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1.

A LURE

Who's pimping who?

—PRINCE

A HEAP OF PIEDMONT white truffles (*Tuber magnatum*) sat on the scales on a check-patterned rag. They were scruffy, like unwashed stones; irregular, like potatoes; socketed, like skulls. Two kilograms: €12,000. Their sweet funk filled the room, and in this aroma was their value. It was unabashed and quite unlike anything else: a lure, thick and confusing enough to get lost in.

It was early November, the height of truffle season, and I had traveled to Italy to join two truffle hunters working out of the hills around Bologna. I was lucky. A friend of a friend knew a man who dealt truffles. The dealer had agreed to set me up with his two best hunters, who in turn had consented to let me go out with them. White-truffle hunters are famously secretive. These fungi have never been domesticated and can only be found in the wild.

Truffles are the underground fruiting bodies of several types of mycorrhizal fungi. For most of the year, truffle fungi exist as mycelial networks, sustained in part by the nutrients they obtain from the soil and also by the sugars they draw from plant roots. However, their subterranean habitat confronts them with a basic problem. Truffles are spore-producing organs, analogous to the seed-producing fruit of a plant. Spores evolved to allow fungi to disperse themselves, but underground their spores can't be caught by air currents and are invisible to the eyes of animals.

Their solution is to smell. But to smell above the olfactory racket of a forest is no small task. Forests are crisscrossed with smells, each a potential fascination or distraction to an animal nose. Truffles must be pungent enough for their scent to penetrate the layers of soil and enter the air, distinctive enough for an animal to take note amid the ambient smellscape, and delicious enough for that animal to seek it out, dig it up, and eat it. Every visual disadvantage that truffles face—being entombed in the soil, difficult to spot once unearthed, and visually unappealing once spotted—they make up for with smell.

Once eaten, a truffle's job is done: An animal has been lured into exploring the soil and recruited to carry the fungus's spores off to a new place and deposit them in its feces. A truffle's allure is thus the outcome of hundreds of thousands of years of evolutionary entanglement with animal tastes. Natural selection will favor truffle fungi that match the preferences of their finest spore dispersers. Truffles with better "chemistry" will attract animals more successfully than those with worse. Like the orchids that mimic the appearance of sexually receptive female bees, truffles provide a depiction of animal tastes—an evolutionary portrait in scent of animal fascination.

I was in Italy because I wanted to be drawn underground by a fungus into the chemical world in which it lived. We are ill-equipped to participate in the chemical lives of fungi, but ripe truffles speak a language so piercing and simple that even we can understand it. In doing so, these fungi include us for a moment within their chemical ecology. How should we think about the torrents of interaction that occur between organisms underground? How should we understand these spheres of more-than-human communication? Perhaps running after a dog hot on the trail of a truffle and burying my face in the soil was as close as I could get to the chemical tug and promise that fungi use to conduct so many aspects of their lives.

Piedmont white truffle, *Tuber magnatum*

—

THE HUMAN SENSE of smell is extraordinary. Our eyes can distinguish several million colors, our ears can distinguish half a million tones, but our noses can distinguish well over a trillion different odors. Humans can detect virtually all volatile chemicals ever tested. We outperform rodents and dogs in detecting certain odors, and we can follow scent trails. Smells feature in our choice of sexual partners and in our ability to detect fear, anxiety, or aggression in others. And smell is woven into the fabric of our memories; it is common for people suffering from post-traumatic stress disorder to have olfactory flashbacks.

Noses are finely tuned instruments. Your olfactory sense can split complex mixtures into their constituent chemicals, just as a prism can split white light into its constituent colors. To do this, it must detect the precise arrangement of atoms within a molecule. Mustard smells mustardy because of bonds between nitrogen, carbon, and sulfur. Fish smells fishy because of bonds between nitrogen and hydrogen. Bonds between carbon and nitrogen smell metallic and oily.

The ability to detect and respond to chemicals is a primordial sensory ability. Most organisms use their chemical senses to explore and make sense of their environment. Plants, fungi, and animals all use similar types of receptors to detect chemicals. When molecules bind to these receptors, they trigger a signaling cascade: One molecule triggers a cellular change, which triggers a bigger change, and so on. In this way, small causes can ripple into large effects: Human noses can detect some compounds at as low a concentration as thirty-four thousand molecules in one square centimeter, the equivalent of a single drop of water in twenty thousand Olympic swimming pools.

For an animal to experience a smell, a molecule must land on their olfactory epithelium. In humans, this is a membrane up and behind the nose. The molecule binds to a receptor, and nerves fire. The brain gets involved as chemicals are identified or trigger thoughts and emotional responses. Fungi are equipped with different kinds of bodies. They don't have noses or brains. Instead, their entire surface behaves like an olfactory epithelium. A mycelial network is one large chemically sensitive membrane: A molecule can bind to a receptor anywhere on its surface and trigger a signaling cascade that alters fungal behavior.

Fungi live their lives bathed in a rich field of chemical information. Truffle fungi use chemicals to communicate to animals their readiness to be eaten; they also use chemicals to communicate with plants, animals, other fungi—and themselves. It isn't possible to understand fungi without exploring these sensory worlds, but they are hard for us to interpret. Perhaps it doesn't matter. Like fungi, we spend much of our lives being drawn toward things. We know what it is to be attracted or repelled. Through smell, we can participate in the molecular discourse fungi use to organize much of their existence.

—

IN HUMAN HISTORY, truffles have long been associated with sex. The word for truffle in many languages translates to "testicle," as in the old Castilian *turmas de tierra*, or Earth's testicles. Truffle fungi have evolved to make animals giddy because their lives depend on it. As I spoke with Charles

Lefevre, a truffle scientist and cultivator in Oregon, about his work with the Périgord black truffle, he broke off: “Funny—as I’m saying this I am ‘bathing’ in the virtual aroma of *Tuber melanosporum*. It’s as if a cloud of it is filling my office, but there are currently no truffles here. These olfactory flashbacks are common with truffles in my experience. They can even include visual and emotional memories.”

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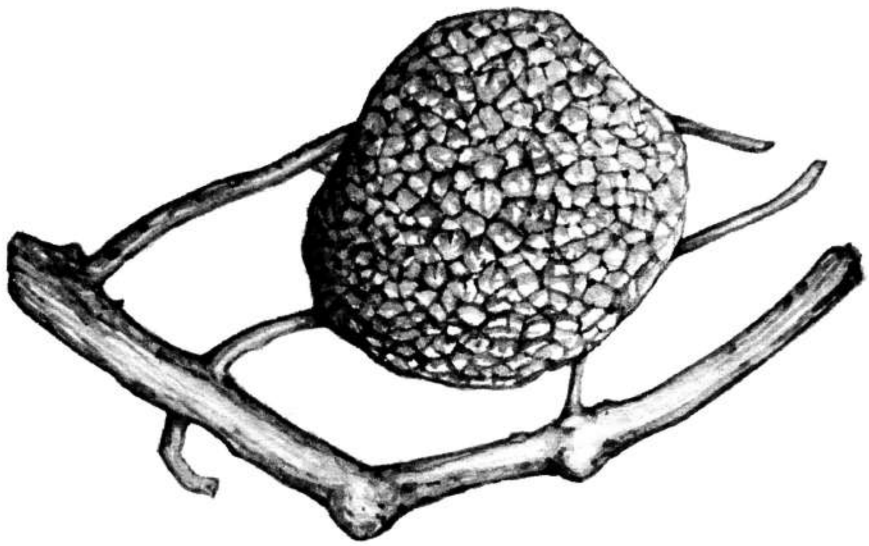


Périgord black truffle, *Tuber melanosporum*

In France, Saint Anthony—the patron saint of lost objects—is regarded as the patron saint of truffles, and truffle masses are celebrated in his honor. Prayers do little to stop the skulduggery. Cheap truffles are stained or flavored to pass them off as their more valuable cousins. Prized truffle forests are targeted by truffle poachers. Expertly trained dogs worth thousands of euros are stolen. Poisoned meat is strewn around woods to kill the dogs of rival hunters. In 2010, in a crime of passion, a French truffle farmer, Laurent Rambaud, shot dead a truffle thief he encountered while patrolling his truffle orchards during the night. Following his arrest, two hundred and fifty supporters marched in support of Rambaud’s right to defend his crop, angry at the rise in thefts of both truffles and truffle dogs. The deputy head of the Tricastin truffle growers’ union told *La Provence* newspaper that he had advised fellow producers never to patrol their fields with a gun because "the temptation is too high." Lefevre put it well: "Truffles bring out the dark side of people. It's like money lying on the ground, but it's perishable and mercurial."

Truffles are not the only fungi to attract animal attention. On the West Coast in North America, bears upend logs and dig out ditches looking for the prized matsutake mushroom. Oregon mushroom hunters have reported elk with noses bloodied in their hunt for matsutake in sharp pumice soils. Some species of tropical rainforest orchid have evolved to mimic the smell, shape, and color of mushrooms to attract mushroom-loving flies. Mushrooms and other fruit bodies are fungi at their most conspicuous, but mycelium, too, can be a lure. A friend of mine who studies tropical insects showed me a video of orchid bees crowding around a crater in a rotting log. Male orchid bees collect scents from the world and amass them into a cocktail that they use to court females. They are perfume makers. Mating takes seconds, but gathering and blending their scents takes their entire adult lives. Although he hadn't yet tested the hypothesis, my friend had a strong hunch that the bees were harvesting fungal compounds to add to their bouquets. Orchid bees are known to have a taste for complex aromatic chemicals, many of which are produced by fungi that break down wood.

Humans wear perfumes produced by other organisms and it is not uncommon for fungal aromas to be incorporated into our own sexual rituals. Agarwood, or oudh, is a fungal infection of *Aquilaria* trees found in India and Southeast Asia and one of the most valuable raw materials in the world. It is used to make a scent—dank nuts, dark honey, rich wood—and has been coveted at least since the time of the ancient Greek physician Dioscorides. The best oudh is worth more, gram for gram, than gold or platinum—as much as $100,000 per kilogram—and the destructive harvest of *Aquilaria* trees has driven them to near extinction in the wild.

The eighteenth-century French physician Théophile de Bordeu asserted that each organism "does not fail to spread exhalations, an odor, emanations around itself…These emanations have taken on its style and its demeanor; they are, in fact, genuine parts of itself." A truffle's fragrance and an orchid bee's perfume may circulate beyond the flesh of each organism, but these fields of odor make up a part of their chemical bodies that overlap with one another like ghosts at a disco.

—

I SPENT SEVERAL minutes in the truffle weighing room, lost in the aroma. My reverie was interrupted when my host, Tony, the truffle dealer, bustled in with one of his clients. He closed the door behind him, sealing in the smell. The client inspected the heap of truffles on the scales and cast an eye over the bowls of unsorted and uncleaned specimens ranged across a grubby workbench. He nodded to Tony, who tied up the corners of the rag. They walked out into the yard, shook hands, and the client drove off in a smart black car.

It had been a dry summer, which had resulted in a poor truffle harvest. The price reflected the scarcity. Bought directly from Tony, a kilogram would set you back €2,000. The same kilogram purchased at a market or restaurant would cost as much as €6,000. In 2007, a single 1.5 kilogram truffle was sold at auction for £165,000—like diamonds, the price of truffles increases nonlinearly with their size.

Tony had a warm manner and a dealer's bravado. He seemed surprised that I would want to join his hunters and didn't get my hopes up about our chances of finding any truffles. "You can go out with my guys, but you probably won't find anything. And it's hard work. Up and down. Through bushes. Through mud. Through streams. Are those the only shoes you have?" I assured him I didn't mind.

Truffle hunters have their turf, sometimes legal, sometimes not. When I arrived, both truffle hunters—Daniele and Paride—were wearing camouflage. I asked whether it helped them to sneak up on the truffles, and they responded in earnest. It allowed them to hunt for truffles without being followed by other truffle hunters. Truffle hunters are in the business of knowing where to look. Their knowledge has value, and, like truffles themselves, can be stolen.

Paride was the friendlier of the two and met me outside with Kika, his favorite truffle dog. He had five dogs of various ages and states of training, each a specialist in either black or white truffles. Kika was charming, and

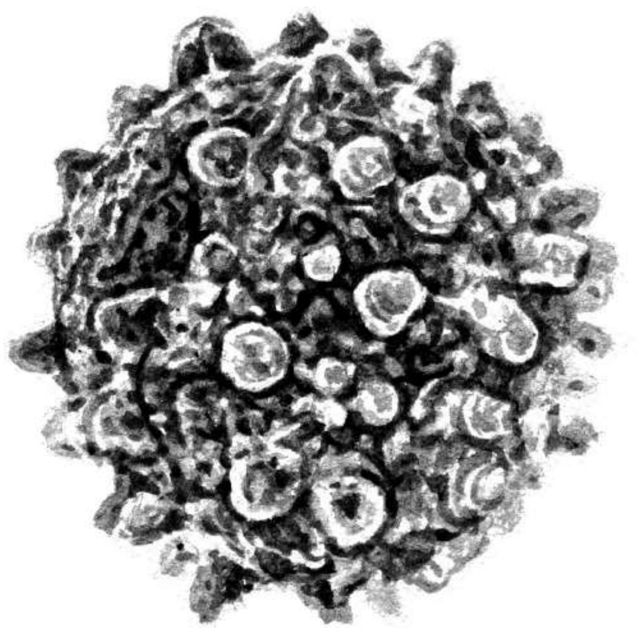
Paride introduced her proudly. “My dog is very clever, but I am more clever.” Kika’s breed—the Lagotto Romagnolo—is one of the most commonly used for truffle hunting. She was knee-height, and with hair that fell over her eyes in shaggy ringlets, she resembled a truffle. Indeed, after a morning smelling truffles, meeting a litter of truffle-dog puppies, talking truffles, witnessing truffle deals, and eating truffles, even the rounded rocky hills had started to look like truffles. Paride spoke about the subtle cues he and Kika used to communicate with each other. They had learned to read and interpret the tiniest shifts in the other’s behavior and could coordinate their movements in near-total silence. Truffles had evolved to communicate to animals their readiness to be eaten. Humans and dogs had developed ways to communicate with one another about truffles’ chemical propositions.

A truffle’s aroma is a complex trait and seems to emerge out of the relationships the truffle maintains with its community of microbes, and the soil and climate it lives within—its terroir. Truffle fruiting bodies house thriving communities of bacteria and yeasts—between a million and a billion bacteria per gram of dry weight. Many members of truffles’ microbiomes are able to produce the distinctive volatile compounds that contribute to truffles’ aromas, and it is likely that the cocktail of chemicals that reaches your nose is the work of more than a single organism.

The chemical basis of truffles’ allure remains uncertain. In 1981, a study published by German researchers found that both Piedmont white truffles (*Tuber magnatum*) and Périgord black truffles (*Tuber melanosporum*) produced androstenol—a steroid with a musky scent—in non-negligible quantities. In pigs, androstenol functions as a sex hormone. It is produced by males and prompts the mating posture in sows. This finding triggered speculation that androstenol might explain the impressive abilities of sows to find truffles buried deep underground. A study published nine years later cast doubt on this possibility. Researchers buried black truffles, a synthetic truffle flavoring, and androstenol five centimeters underground, and challenged a pig and five dogs—including the champion of the local county truffle-dog contest—to find the samples. All the animals detected the real truffles and the synthetic truffle flavoring. None detected the androstenol.

In a series of further tests, the researchers narrowed truffles' allure down to a single molecule: dimethyl sulfide. It was a neat study, but unlikely to be the whole truth. The smell of a truffle is made up of a flock of different molecules drifting in formation—more than a hundred in white truffles and around fifty in the other most popular species. These elaborate bouquets are energetically costly and are unlikely to have evolved unless they served some purpose. What's more, animal tastes are diverse. Certainly, not all truffle species are attractive to humans and some are even mildly poisonous. Of the thousand-odd species of truffle in North America, only a handful are of culinary interest. Even these aren't of interest to everyone. As Lefevre explained, a large number of people are offended by the aroma of the otherwise prized species. Some species smell outright repulsive. He told me about *Gautieria,* a genus that produces truffles with a foul stench—like "sewer gas" or "baby diarrhea." His dogs love them, but his wife won't let him bring any into the house, even for taxonomic purposes.

However they do it, truffles create nested layers of attraction around themselves: Humans train dogs to find truffles because pigs are so attracted to them that they devour the truffles they find rather than turn them over to their minders. Restaurateurs from New York and Tokyo travel to Italy to build relationships with truffle dealers. Exporters have developed sophisticated chilled packing systems to maintain truffles at optimal conditions as they are washed, packed, hand-delivered to the airport, flown around the world, collected from the airport, carried through customs, repacked, and distributed to consumers—all within forty-eight hours. Truffles, like matsutake mushrooms, must arrive fresh on a plate within two to three days of harvest. Truffles' aromas are made in an active process by living, metabolizing cells. A truffle's odor increases as its spores develop, and its aroma ceases when its cells die. You can't dry a truffle and expect to taste it later, as you can with some types of mushroom. They are chemically loquacious, vociferous even. Stop the metabolism, and you stop the smell. For this reason, in many restaurants, fresh truffles are grated onto your food before your eyes. Few other organisms are so good at persuading humans to disperse them with such urgency.



Truffle spore

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WE PILED INTO Paride's car and drove up a valley on a narrow country road, through the damp yellows and browns of the oak woods that covered the hills. Paride talked about the weather and cracked jokes about dog training and the pros and cons of working with a "bandit" like Daniele. After a few minutes, we turned down a track and pulled over. Kika jumped out of the trunk, and we walked along a meadow and into a wood. Daniele had already arrived and was hovering furtively with his dog. There was another truffle hunter nearby, he explained, and we had to be quiet. Daniele's dog was tousled and unkempt and had twigs caught in its curls. It didn't have a name, although Paride said that he had heard Daniele call it Diavolo (Devil) earlier that morning. Unlike Kika, who was affectionate and friendly, Diavolo had a tendency to snap and snarl. Paride explained why. Whereas he trained his dogs to hunt for truffles as if it were a game, Daniele trained his by hunger. "Look," Paride pointed at Diavolo, "it's desperate, it's eating acorns.” They bantered for a while. Daniele argued that his dogs were more effective truffle hunters than Paride’s well-fed and well-loved “pets.” Paride stuck up for the reformed school of truffle-dog training, summing it up neatly: “Daniele hunts truffles at night, and I hunt them in the day. He is nervous, and I am not. His dog bites, and mine is friendly. His dog is slim, and mine is not slim. He is bad, and I am good.”

All of a sudden, Diavolo darted off. We followed him, Paride providing a commentary as we scrambled along. “There may be a truffle. Or a mouse. Either way the dog’s happy.” We found Diavolo digging and snorting halfway up a muddy bank. Daniele caught up and cleared away the brambles. At this point, Paride explained, the truffle hunter had to read the dog’s body language closely. A wagging tail promised truffles, a still tail suggested otherwise. A two-pawed dig indicated white truffles, a one-pawed dig black. The signs looked good, and Daniele began to loosen the soil with a blunt, flat-tipped tool like a giant screwdriver, smelling pinches of soil as he got deeper. He and the dog took it in turns, though he was careful to stop Diavolo digging too vigorously. Paride smiled over at us: “A hungry dog eats the truffle.”

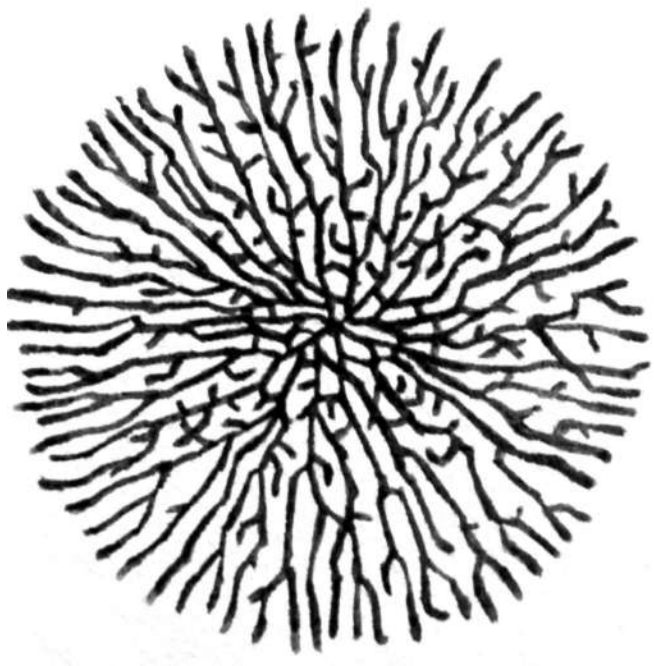
Finally, about a foot and a half down, Daniele found it lodged in the damp soil. With his fingers and a small metal hook, he pulled away the mud. The truffle’s aroma strayed upward from the hole, brighter and more saturated than in the weighing room. This was its natural habitat, and its scent drifted in easy harmony with the dampness of the ground and the fraying of leaf mold. I imagined being sensitive enough to notice the truffle’s aroma at a distance and compelled enough to drop everything to pursue it. Inhaling its emanations I recalled the passage in Aldous Huxley’s *Brave New World* where he describes the performance of a scent organ, an instrument able to give olfactory recitals in the way a musical instrument might. It is a concept easily adapted for truffles—scent organs in a different sense—that perform, in their way, suites of volatile compounds.

How well it had worked. Here we all were, tousled and muddy, standing around a truffle. It had triggered a signaling cascade, tugging a troupe of animals toward it—first a dog, then a truffle-hunting human, then his slower-footed associates. As Daniele picked up the truffle, the ground around it collapsed. “Look!” Paride cleared the soil aside. “The house of a mouse.” We had not been the first to arrive.

—

WHEN WE SMELL a truffle’s aroma, we receive a one-way transmission from truffle to world. The process is comparatively nuance-free. To attract an animal the aroma has to be curious, and delicious—yes. But most of all it has to be penetrating and strong. It doesn’t really matter whether their spores are scattered by a wild boar or a flying squirrel, so why be picky? Most hungry animals will chase a delicious smell. Moreover, a truffle doesn’t change its aroma in response to your immediate attentions. It can excite, but it isn’t excitable. Its signal billows out loud and clear, and once begun, it is always on. A ripe truffle broadcasts an unambiguous summons in chemical lingua franca, a pop scent with mass appeal that could cause Daniele, Paride, two dogs, a mouse, and me to converge at a single point under a bramble bush on a muddy bank in Italy.

Truffles—like many other highly prized fungal fruiting bodies—are their parent fungus’s least sophisticated channels of communication. Much of fungal life, including the growth of mycelium, depends on subtler forms of allure. There are two key moves by which fungal hyphae become a mycelial network. First, they branch. Second, they fuse. (The process by which hyphae merge with each other is known as “anastomosis,” which in Greek means “to provide with a mouth.”) If hyphae couldn’t branch, one hypha could never become many. If hyphae couldn’t fuse with one another, they would not be able to grow into complex networks. However, before they fuse, hyphae must find other hyphae, which they do by attracting one another, a phenomenon known as “homing.” Fusion between hyphae is the linking stitch that makes mycelium mycelium, the most basic networking act. In this sense, the mycelium of any fungus arises from its ability to attract itself to itself.



Mycelium growing outward from a spore. Redrawn from Buller, 1931.

However, much as a given mycelial network is able to encounter itself, it is able to encounter another. How do fungi maintain a sense of a body subject to continual revision? Hyphae must be able to tell if they are bumping into a branch of themselves or another fungus entirely. If another, they need to be able to tell whether it is a different—potentially hostile—species, or a sexually compatible member of its own, or neither. Some fungi have tens of thousands of mating types, approximately equivalent to our sexes (the record holder is the split gill fungus, *Schizophyllum commune*, which has more than twenty-three thousand mating types, each of which is sexually compatible with nearly every one of the others). The mycelium of many fungi can fuse with other mycelial networks if they are genetically similar enough, even if they aren't sexually compatible. Fungal self-identity matters, but it is not always a binary world. Self can shade off into otherness gradually.

Allure underpins many types of fungal sex, including that of truffle fungi. Truffles themselves are the outcome of a sexual encounter: For a truffle fungus like *Tuber melanosporum* to fruit, the hyphae of one mycelial network must fuse with those of a separate, sexually compatible network and pool genetic material. For most of their lives, as mycelial networks, truffle fungi live as separate mating types, whether "-" or "+"—by fungal standards, their sexual lives are straightforward. Sex happens when a - hypha attracts and fuses with a + hypha. One partner plays a paternal role, providing genetic material only. The other plays a maternal role, providing genetic material and growing the flesh that matures into truffles and spores. Truffles differ from humans in that either + or - mating types can be maternal or paternal—it is as if all humans were both male and female and equally able to play the part of a mother or a father, provided we could have sex with a partner of the opposite mating type. How the sexual attraction between truffle fungi plays out remains unknown. Closely related fungi use pheromones to attract mates, and researchers have a strong suspicion that truffles, too, use a sex pheromone for this purpose.

Without homing, there could be no mycelium. Without mycelium, there could be no attraction between - and + mating types. Without sexual attraction there could be no sex. And without sex, there could be no truffle. However, the relationships between truffle fungi and their partner trees are just as important, and their chemical interactions must be intricately managed. The hyphae of young truffle fungi will soon die unless they find a plant to partner with. Plants must admit into their roots the fungal species that will form a mutually beneficial relationship, as opposed to the many that will cause disease. Both fungal hyphae and plant roots face the challenge of finding one another amid the chemical babble in the soil where countless other roots, fungi, and microbes course and engage.

It is another case of attraction and allure, of chemical call-and-response. Both plant and fungus use volatile chemicals to make themselves attractive to one another, just as truffles make themselves attractive to animals in a forest. Receptive plant roots produce plumes of volatile compounds that drift through the soil and cause spores to sprout and hyphae to branch and grow faster. Fungi produce plant growth hormones that manipulate roots, causing them to proliferate into masses of feathery branches—with a greater surface area, the chances of an encounter between root tips and fungal hyphae become more likely. (Many fungi produce plant and animal hormones to alter the physiology of their associates.)

More than the architecture of roots has to change for a fungus to bond with a plant. In response to each other's distinctive chemical profiles, signaling cascades ripple through plant and fungal cells, activating suites of genes. Both reorient their metabolisms and developmental programs. Fungi release chemicals that suspend their plant partners' immune responses, without which they can't get close enough to form symbiotic structures. Once established, mycorrhizal partnerships continue to develop. Connections between hyphae and roots are dynamic, formed and reformed as root tips and fungal hyphae get old and die. These are relationships that ceaselessly remodel themselves. If you could place your olfactory epithelium into the soil, it would feel like the performance of a jazz group, with the players listening, interacting, responding to one another in real time.

Piedmont white truffles and other prized mycorrhizal fungi, such as porcini, chanterelle, and matsutake, have never been domesticated in part because of the fluidity of their relationships with plants, and in part because of the intricacies of their sex lives. There are too many gaps in our understanding of how basic fungal communication happens. Some truffle species can be cultivated, such as the Périgord black, but trufficulture is immature by comparison with the venerable craft surrounding most human agricultural efforts, and even the success of seasoned cultivators can vary wildly. At Lefevre's New World Truffieres, the proportion of seedlings that grow successfully with the mycelium of the Périgord black truffle hovers around thirty percent. One year, with no deliberate change in method, he achieved a one hundred percent success rate. "I have not been able to reproduce that result," he told me. "I don't know what I did right."

To cultivate truffles effectively, you have to understand the quirks and needs not only of the fungi—with their idiosyncratic reproductive systems—but also of the trees and bacteria they live with. Moreover, you have to understand the importance of subtle variations in the surrounding soil, season, and climate. "It is an intellectually stimulating field because it's so interdisciplinary," Ulf Büntgen, a professor of geography at Cambridge, and the first to report the fruiting of a Périgord black truffle in the British Isles, told me. "It is microbiology, physiology, land management, agriculture, forestry, ecology, economy, and climate change. You really have to take a holistic perspective." Truffles' affairs quickly unspool into entire ecosystems. Scientific understanding hasn't yet caught up.

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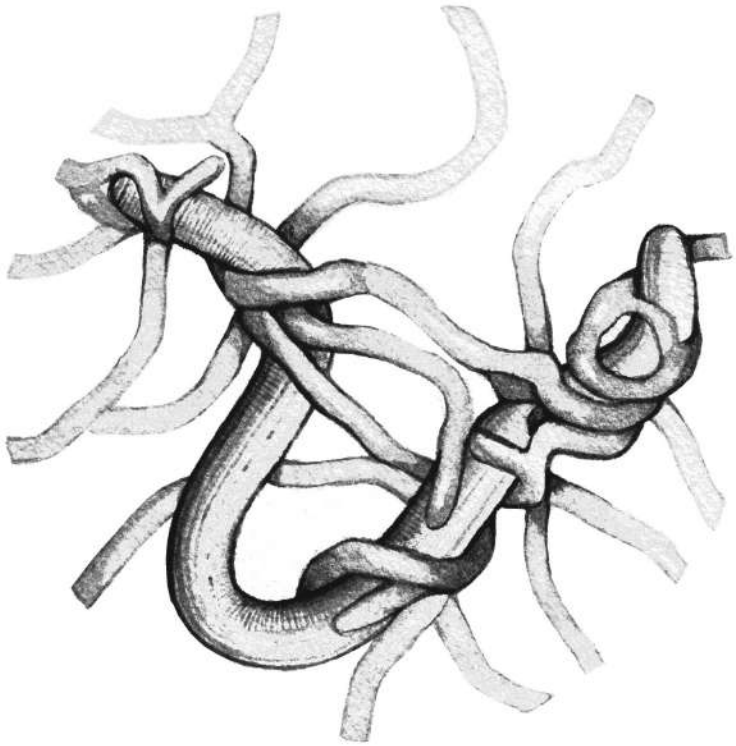
For some attracted by fungal chemical allure, the outcome is simpler: death.

Among the most impressive sensory feats are those performed by predatory fungi that trap and consume nematode worms. Hundreds of species of worm-hunting fungi can be found all over the world. Most spend their lives decomposing plant matter and only start to hunt when there is insufficient material to eat. But they're subtle predators: Unlike truffles, whose scent, once begun, is always on, nematode-eating fungi only produce worm-hunting organs and issue a chemical summons when they sense nematodes are close by. If there is plenty of material to rot, they don't bother, even if worms abound. To behave in this way, nematode-eating fungi must be able to detect the presence of worms with exquisite sensitivity. Nematodes all depend on the same class of molecule to serve a number of purposes, from regulating their development to attracting mates. In turn, fungi use these chemicals to eavesdrop on their prey.

The methods fungi use to hunt nematodes are grisly and diverse. It is a habit that has evolved multiple times—many fungal lineages have reached a similar conclusion but in different ways. Some fungi grow adhesive nets, or branches to which nematodes stick. Some use mechanical means, producing hyphal nooses that inflate in a tenth of a second when touched, ensnaring their prey. Some—including the commonly cultivated oyster mushroom (*Pleurotus ostreatus*)—produce hyphal stalks capped with a single toxic droplet that paralyzes nematodes, giving the hypha enough time to grow through their mouth and digest the worm from the inside. Others produce spores that can swim through the soil, chemically drawn toward nematodes, to which they bind. Once attached, the spores sprout and the fungus harpoons the worm with specialized hyphae known as "gun cells."

Fungal worm-hunting is a variable behavior: Different individuals of a given species can respond idiosyncratically, producing different types of trap, or positioning traps in distinctive ways. One species—*Arthrobotrys oligospora*—behaves like a "normal" decomposer in the presence of plenty of organic material and, if needs be, can produce nematode traps in its mycelium. It can also coil around the mycelium of other types of fungi, starving them, or develop specialized structures to penetrate and feed off plant roots. How it chooses between its many options remains unknown.



Nematode worm being devoured

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HOW SHOULD WE talk about fungal communication? In Italy, as we crowded around the hole in the muddy bank, peering in, I tried to imagine the scene from the truffle's point of view. In the excitement, Paride offered a lyrical interpretation. "The truffle and its tree are like lovers, or husband and wife," he crooned. "If the threads are broken, there can be no going back. The bond is gone forever. The truffle was born from the root of the tree, defended by the wild rose." He gestured to the brambles. "It lay inside, protected by the thorns like Sleeping Beauty, waiting to be kissed by the dog."

The prevailing scientific view is that it is a mistake to imagine that there is anything deliberate about most nonhuman interactions. Truffle fungi are not articulate. They don't speak. Like many of the animals and plants they depend on, truffle fungi react to their environment automatically, based on robotic routines that maximize their chance of survival. In stark contrast is the vivid experience of human life, where the quantity of a stimulus glides seamlessly into the quality of sensation; where stimuli are felt and arouse emotion; where we are affected.

I balanced on the muddy slope and suspended my nose over the pungent clod of fungus. No matter how hard I tried to reduce the truffle to an automaton, it kept springing to life in my mind.

When trying to understand the interactions of nonhuman organisms, it is easy to flip between these two perspectives: that of the inanimate behavior of preprogrammed robots on the one hand, and that of rich, lived human experience on the other. Framed as brainless organisms, lacking the basic apparatus required to have even a simple kind of "experience," fungal interactions are no more than automatic responses to a series of biochemical triggers. Yet the mycelium of truffle fungi, like that of most fungal species, actively senses and responds to its surroundings in unpredictable ways. Their hyphae are chemically irritable, responsive, excitable. It is this ability to interpret the chemical emissions of others that allows fungi to negotiate a series of complex trading relationships with trees; to knead away at stores of nutrients in the soil; to have sex; to hunt; or to fend off attackers.

Anthropomorphism is usually thought of as an illusion that arises like a blister in soft human minds: untrained, undisciplined, unhardened. There are good reasons for this: When we humanize the world, we may prevent ourselves from understanding the lives of other organisms on their own terms. But are there things this stance might lead us to pass over—or forget to notice?

The biologist Robin Wall Kimmerer, a member of the Citizen Potawatomi Nation, observes that the indigenous Potawatomi language is rich in verb forms that attribute aliveness to the more-than-human world. The word for "hill," for example, is a verb: to be a hill. Hills are always in the process of hilling, they are actively *being* hills. Equipped with this "grammar of animacy," it is possible to talk about the life of other organisms without either reducing them to an "it" or borrowing concepts traditionally reserved for humans. By contrast, in English, writes Kimmerer, there is no way to recognize the "simple existence of another living being."

If you're not a human *subject*, by default you're an inanimate *object:* an "it," a "mere thing." If you repurpose a human concept to help make sense of the life of a nonhuman organism, you've tumbled into the trap of anthropomorphism. Use "it," and you've objectified the organism and fallen into a different kind of trap.

Biological realities are never black-and-white. Why should the stories and metaphors we use to make sense of the world—our investigative tools—be so? Might we be able to expand some of our concepts, such that speaking might not always require a mouth, hearing might not always require ears, and interpreting might not always require a nervous system? Are we able to do this without smothering other life-forms with prejudice and innuendo?

Daniele wrapped up the truffle and carefully filled in the hole, pulling the clump of brambles back over the turned earth. Paride explained that it was to avoid disturbing the fungus's relationship with its tree's roots. Daniele said that it was to prevent other truffle hunters from following in our tracks. We strolled back through the field. The truffle's smell was less vivid by the time we arrived at the car and more muted still by the time we got back to the weighing room. I wondered how faint it would be by the time it was grated onto a plate in Los Angeles.

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SOME MONTHS LATER, in the wooded hills outside Eugene, Oregon, I went out truffle hunting with Lefevre and his Lagotto Romagnolo, Dante. Dante is what Lefevre calls a diversity dog. Production dogs—like Kika and Diavolo—are trained to find large amounts of a particular species; diversity dogs are trained to go after anything that smells interesting. This allows them to find species of truffle they have never smelled before. As a result Dante sometimes chases things that aren't truffles—pungent millipedes, for instance—but he has also unearthed four undescribed species of truffle. This is not so uncommon. Mike Castellano, a renowned truffle expert with a species named after him—he has described two new orders, more than two dozen new genera, and some two hundred new species of truffle—reports routinely discovering new species of truffle when collecting in California, a reminder of how much remains unknown.

As we ambled through the Douglas firs and sword ferns, Lefevre explained that humans have been cultivating truffles unintentionally for centuries. Truffles thrive in the disturbed environments that humans make. In Europe, truffle production plummeted during the twentieth century as the truffle-growing heartlands of managed woodland were either cleared for agriculture or abandoned and left to grow into mature forests. Neither are good for truffle production. For Lefevre, the resurgence of trufficulture is exciting because it is a way to produce a cash crop from a forested landscape and divert private capital into environmental restoration. To grow truffles, you have to grow trees. You have to acknowledge that the soil is full of life. You can't cultivate truffles without thinking at the level of the ecosystem.

Dante zigzagged around, sniffing. Lefevre told me about the theory that manna—the providential food that sustained the Israelites during their passage through the desert—was in fact the desert truffle, a delicacy that erupts without warning from arid ground across much of the Middle East. He told me about his unsuccessful attempts to cultivate the evasive white truffle and how little we understand about its relationship to its host trees. I thought of the many ways that fungi respond to changing environments and find new ways to live alongside the plants and animals on which they depend.

Back in a forest, hunting for truffles, I found myself once again searching for language to describe the lives of these remarkable organisms. Perfumers and wine tasters use metaphors to articulate differences in aromas. A chemical becomes "cut grass," "sweaty mango," "grapefruit and hot horses." Without these references, we would be unable to imagine it. Cis-3-hexenol smells like cut grass. Oxane smells like sweaty mango. Gardamide smells like grapefruit and hot horses. This is not to say oxane *is* sweaty mango, but if I were to pass you an open vial you'd almost certainly recognize the smell. Correlating human language with an odor involves judgment and prejudice. Our descriptions warp and deform the phenomena we describe, but sometimes this is the only way to talk about features of the world: to say what they are like but are not. Might this also be the case when we talk about other organisms?

Boil it down and there aren't many other options. Fungi may not have brains, but their many options entail decisions. Their fickle environments entail improvisation. Their trials entail errors. Whether in the homing response of hyphae within a mycelial network, the sexual attraction between two hyphae in separate mycelial networks, the vital fascination between a mycorrhizal hypha and a plant root, or the fatal attraction of a nematode to a fungal toxic droplet, fungi actively sense and interpret their worlds, even if we have no way of knowing what it is *like* for a hypha to sense or interpret. Perhaps it isn't so strange to think of fungi as articulating themselves using a chemical vocabulary, arranged and rearranged in such a way that it might be interpreted by other organisms, whether nematode, tree root, truffle dog, or New York restaurateur. Sometimes—as with truffles—these molecules might translate into a chemical language we can, in our way, understand. The vast majority will always pass over our heads, or under our feet.

Dante started digging furiously. "It looks like a truffle," Lefevre said, reading the dog's body language, "but it's deep." I asked whether he ever worried about Dante's nose or feet getting hurt from all the frantic digging. "Oh he does keep injuring his pads," Lefevre admitted. "I keep meaning to get him some booties." Dante snorted and scraped, but to no avail. "I feel bad not rewarding him for his efforts when he's unsuccessful"—Lefevre crouched down and ruffled his curls—"but I haven't found a treat that's worth more to him than a truffle. Truffles trump everything." He grinned up at me. "For Dante, God lives just below the surface of the soil."

2.

LIVING LABYRINTHS

I am so happy in the silky
damp dark of the labyrinth
and there is no thread.

—HÉLÈNE CIXOUS

IMAGINE THAT YOU could pass through two doors at once. It's inconceivable, yet fungi do it all the time. When faced with a forked path, fungal hyphae don't have to choose one or the other. They can branch and take both routes.

One can confront hyphae with microscopic labyrinths and watch how they nose their way around. If obstructed, they branch. After diverting themselves around an obstacle, the hyphal tips recover the original direction of their growth. They soon find the shortest path to the exit, just as my friend's puzzle-solving slime molds were able to find the quickest way out of the IKEA maze. If one follows the growing tips as they explore, it does something peculiar to one's mind. One tip becomes two, becomes four, becomes eight—yet all remain connected in one mycelial network. Is this organism singular or plural, I find myself wondering, before I'm forced to admit that it is somehow, improbably, *both*.

Watching a hypha explore a single clinical maze is bewildering, but scale up: Imagine millions of hyphal tips, each navigating a different maze at the same time within a tablespoon of soil. Scale up again: Imagine billions of hyphal tips exploring a patch of forest the size of a football field.

Mycelium is ecological connective tissue, the living seam by which much of the world is stitched into relation. In school classrooms children are shown anatomical charts, each depicting different aspects of the human body. One chart reveals the body as a skeleton, another the body as a network of blood vessels, another the nerves, another the muscles. If we made equivalent sets of diagrams to portray ecosystems, one of the layers would show the fungal mycelium that runs through them. We would see sprawling, interlaced webs strung through the soil, through sulfurous sediments hundreds of meters below the surface of the ocean, along coral reefs, through plant and animal bodies both alive and dead, in rubbish dumps, carpets, floorboards, old books in libraries, specks of house dust, and in canvases of old master paintings hanging in museums. According to some estimates, if one teased apart the mycelium found in a gram of soil—about a teaspoon—and laid it end to end, it could stretch anywhere from a hundred meters to ten kilometers. In practice, it is impossible to measure the extent to which mycelium perfuses the Earth's structures, systems, and inhabitants—its weave is too tight. Mycelium is a way of life that challenges our animal imaginations.

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LYNNE BODDY, A professor of microbial ecology at Cardiff University, has spent decades studying the foraging behavior of mycelium. Her elegant studies illustrate the problems that mycelial networks are able to solve. In one experiment, Boddy allowed a wood-rotting fungus to grow within a block of wood. She then placed the block on a dish. Mycelium spread radially outward from the block in all directions, forming a fuzzy white circle. Eventually the growing network encountered a new block of wood. Only a small part of the fungus touched the wood, but the behavior of the entire network changed. The mycelium stopped exploring in all directions. It withdrew the exploratory parts of its network and thickened the connection with the newly discovered block. After a few days, the network was unrecognizable. It had completely remodeled itself.

She then repeated the experiment, but with a twist. She let the fungus grow out from the original block and discover the new block of wood. However this time, before the network had time to remodel itself, she removed the original block of wood from the dish, stripped away all of the hyphae growing out of it, and placed it onto a fresh dish. The fungus grew out from the original block in the direction of the newly discovered block. The mycelium appeared to possess a directional memory, although the basis of this memory remains unclear.

Boddy has a no-nonsense manner and talks with quiet amazement about what these fungi are able to do. Their behavior is a bit like that of slime molds, and she has tested them in similar ways. However, rather than modeling the Tokyo underground network, Boddy encouraged mycelium to work out the most efficient routes between the cities of Great Britain. She arranged soil into the shape of the British landmass and marked cities using blocks of wood colonized with a fungus (the sulfur tuft, or *Hypholoma fasciculare*). The size of the wood blocks was proportional to the population of the cities they represented. “The fungi grew out from the ‘cities’ and made the motorway network,” Boddy recounted. “You could see the M5, M4, M1, M6. I thought it was quite fun.”

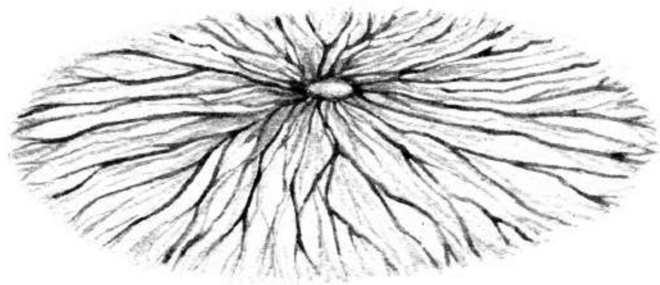
One way to think about mycelial networks is as swarms of hyphal tips. Insects form swarms. A murmuration of starlings is a swarm, as is a school of sardines. Swarms are patterns of collective behavior. Without a leader or command center, a swarm of ants can work out the shortest route to a source of food. A swarm of termites can build giant mounds with sophisticated architectural features. However, mycelium quickly outgrows the swarm analogy because all the hyphal tips in a network are connected to one another. A termite mound is made up of units of termites. A hyphal tip would be the closest we could come to defining the unit of a mycelial swarm, although one can’t dismantle a mycelial network hypha by hypha once it has grown, as we could pick apart a swarm of termites. Mycelium is conceptually slippery. From the point of view of the network, mycelium is a single interconnected entity. From the point of view of a hyphal tip, mycelium is a multitude.

“I think there’s lots we can learn, as humans, from mycelium,” Boddy reflected. “You can’t just go and close a road to see how the traffic flow changes, but you can sever a connection in a mycelial network.” Researchers have begun to use network-based organisms like slime molds and fungi to solve human problems. The researchers who modeled the Tokyo train network using slime molds are working to incorporate slime-mold behavior into the design of urban transportation networks.

Researchers at the Unconventional Computing Laboratory at the University of the West of England have used slime molds to calculate efficient fire evacuation routes from buildings. Some are applying the strategies that fungi and slime molds use to navigate labyrinths to solve mathematical problems or to program robots.

Solving mazes and complex routing problems are nontrivial exercises. This is why mazes have long been used to assess the problem-solving abilities of many organisms, from octopuses to bees to humans. Nonetheless, mycelial fungi are maze-dwellers, and solving spatial and geometrical problems is what they have evolved to do. How best to distribute their bodies is a question fungi face on a moment-to-moment basis. By growing a dense network, mycelium can increase its capacity for transport, but dense networks aren't good for exploring across large distances. Sparse networks are better for foraging across large areas but have fewer interconnections and so are more vulnerable to damage. How do fungi juggle this kind of trade-off while exploring a crowded rotscape in search of food?

Boddy's experiment with two blocks of wood illustrates a typical sequence of events. The mycelium starts in an exploratory mode, proliferating in all directions. Setting out to find water in a desert, we'd have to pick one direction to explore. Fungi can choose all possible routes at once. If the fungus discovers something to eat, it reinforces the links that connect it with the food and prunes back the links that don't lead anywhere. One can think of it in terms of natural selection. Mycelium overproduces links. Some turn out to be more competitive than others. These links are thickened. Less competitive links are withdrawn, leaving a few mainline highways. By growing in one direction while pulling back from another, mycelial networks can even migrate through a landscape. The Latin root of the word *extravagant* means "to wander outside or beyond." It is a good word for mycelium, which ceaselessly wanders outside and beyond its limits, none of which are preset as they are in most animal bodies. Mycelium is a body without a body plan.



Mycelium exploring a flat surface

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HOW DOES ONE part of a mycelial network "know" what is happening in a distant part of the network? Mycelium sprawls, yet must somehow be able to stay in touch—with itself.

Stefan Olsson is a Swedish mycologist who has spent decades trying to understand how mycelial networks coordinate themselves and behave as integrated wholes. A number of years ago, he became interested in one of several species of fungus that produce bioluminescence, which causes their mushrooms and mycelium to glow in the dark and can help attract insects that disperse their spores. Coal miners in nineteenth-century England reported that bioluminescent fungi growing on wooden pit props were bright enough to "see their hands by," and Benjamin Franklin proposed the use of the bioluminescent fungi known as "foxfire" to illuminate the compass and depth gauge of the first submarine (the *Turtle*—developed in 1775 during the American Revolutionary War). The species Olsson had been studying was the bitter oyster, *Panellus stipticus*. "You could read in the light of it when I grew it in jars," he told me. "It was like a little lamp standing on the shelf at home. My kids loved it."

To monitor the behavior of *Panellus* mycelium, Olsson grew cultures in dishes in the lab and placed two of them, glowing, in a perfectly dark box under constant conditions. He left them alone for a week with a camera sensitive enough to detect their bioluminescence taking pictures every few seconds. In the time-lapse video, two unconnected mycelial cultures grow outward into the shape of irregular circles in their separate dishes, glowing more intensely in the middle than at their edges. After several days—about two minutes of video—there is a sudden shift. In one of the cultures, a wave of bioluminescence passes over the network from one edge to the other. A day later, a similar wave passes over the second culture. On mycelial timescales, it is high drama. In a matter of—mycelial—moments, each network flips into a different physiological state.

“What the hell is that?” Olsson exclaimed to me. He jokes that left alone the fungus might have got bored, started playing, or become depressed. Although he left the cultures in the dark for several more weeks, the pulse never happened again. Years later, he still doesn’t have a good explanation for what caused it. Nor for how the mycelium was able to coordinate its behavior over such short timescales.

Mycelial coordination is difficult to understand because there is no center of control. If we cut off our head or stop our heart, we’re finished. A mycelial network has no head and no brain. Fungi, like plants, are decentralized organisms. There are no operational centers, no capital cities, no seats of government. Control is dispersed: Mycelial coordination takes place both everywhere at once and nowhere in particular. A fragment of mycelium can regenerate an entire network, meaning that a single mycelial individual—if you’re brave enough to use that word—is potentially immortal.

Olsson was intrigued by the spontaneous waves of bioluminescence that he had recorded and prepared another set of dishes for a follow-up experiment. He tried stabbing one side of a *Panellus* mycelium with the tip of a pipette. The wounded area lit up immediately. What confused him was that within ten minutes the light had spread a distance of nine centimeters across the whole network. This was far faster than a chemical signal could travel from one side to the other within the mycelium itself.

It occurred to Olsson that the wounded hyphae could have released a volatile chemical signal into the air that spread across the network in a gaseous cloud, thus avoiding the need to travel within the network. He tested this possibility by growing two genetically identical mycelia side by side. There were no direct connections between them, but they were close enough that chemicals drifting through the air would traverse the gap. Olsson stabbed one of the networks. The light propagated across the wounded network as it had before, but the signal did not spread to its neighbor. Some kind of rapid communication system had to be operating within the network itself. Olsson became increasingly preoccupied by the question of what this might be.

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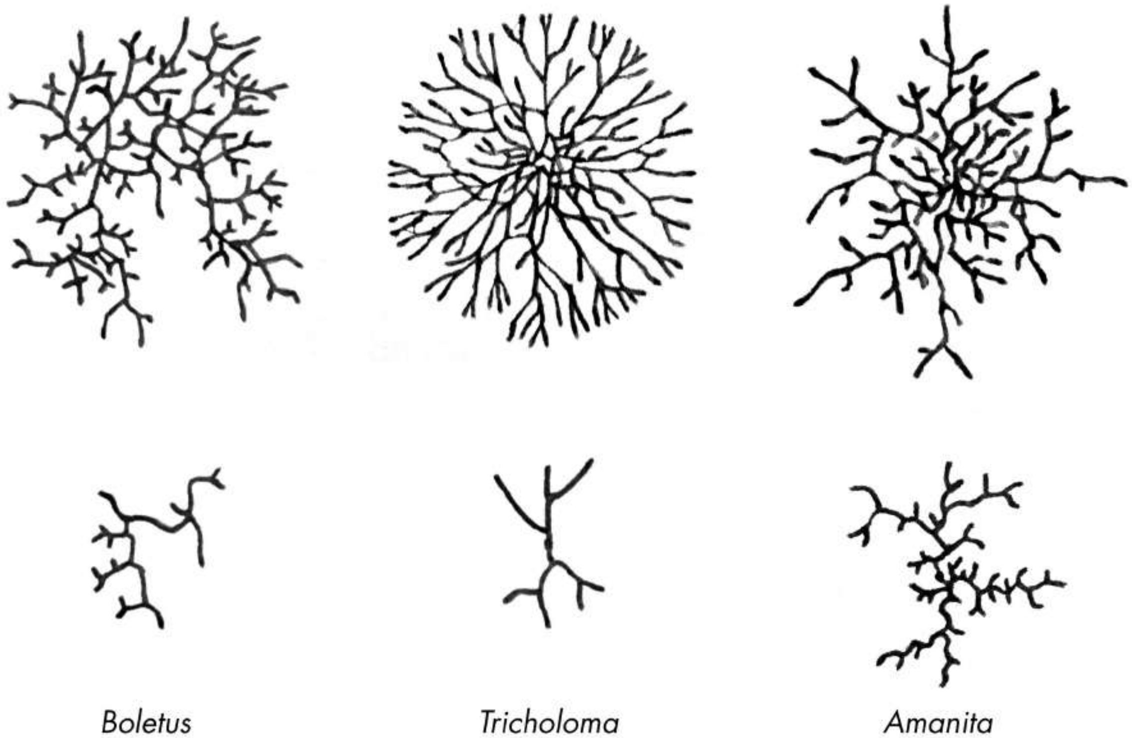
Mycelium is how fungi feed. Some organisms—such as plants that photosynthesize—make their own food. Some organisms—like most animals—find food in the world and put it inside their bodies, where it is digested and absorbed. Fungi have a different strategy. They digest the world where it is and then absorb it into their bodies. Their hyphae are long and branched, and only a single cell thick—between two and twenty micrometers in diameter, more than five times thinner than an average human hair. The more of their surroundings that hyphae can touch, the more they can consume. The difference between animals and fungi is simple: Animals put food in their bodies, whereas fungi put their bodies in the food.

However, the world is unpredictable. Most animals cope with uncertainty by moving. If food can be more easily found elsewhere, they move elsewhere. But to embed oneself in an irregular and unpredictable food supply as mycelium does, one must be able to shape-shift. Mycelium is a living, growing, opportunistic investigation—speculation in bodily form. This tendency is known as developmental “indeterminism”: No two mycelial networks are the same. What shape is mycelium? It’s like asking what shape water is. We can only answer the question if we know where the mycelium happens to be growing. Compare this with humans, all of whom share a body plan and embark on similar developmental journeys. Short of an intervention, if we are born with two arms we will end up with two arms.

Mycelium decants itself into its surroundings, but its growth pattern isn’t infinitely variable. Different fungal species form different kinds of mycelial networks. Some species have thin hyphae, some thick. Some are picky about their food, others less so. Some grow into ephemeral puffs that don’t range beyond their food source and could fit on a single speck of house dust. Other species form long-lived networks that roam over kilometers. Some tropical species don’t forage for food at all. Instead, they behave like filter-feeding animals and grow nets out of thick strands of mycelium, which they use to catch falling leaves.



Different mycelial types. Redrawn after Fries, 1943.

No matter where fungi grow, they must be able to insinuate themselves within their source of food. To do so, they use pressure. In cases where mycelium has to break through particularly tough barriers, as disease-causing fungi do when infecting plants, they develop special penetrative hyphae that can reach pressures of fifty to eighty atmospheres and exert enough force to penetrate the tough plastics Mylar and Kevlar. One study estimated that if a hypha was as wide as a human hand, it would be able to lift an eight-ton school bus.

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MOST MULTICELLULAR ORGANISMS grow by laying down new layers of cells. Cells divide to make more cells which then divide again. A liver is made by piling liver cells on top of liver cells. The same goes for a muscle or a carrot. Hyphae are different; they grow by getting longer. Under the right conditions, a hypha can prolong itself indefinitely.

At a molecular level, all cellular activity, whether fungal or not, is a blur of rapid activity. Even by these standards, hyphal tips are a commotion, busier than a court of ten thousand self-dribbling basketballs. The hyphae of some species grow so fast that one can watch them extend in real time. Hyphal tips must lay down new material as they advance. Small bladders filled with cellular building materials arrive at the tip from within and fuse with it at a rate of up to six hundred a second.

In 1995, the artist Francis Alÿs walked around São Paulo carrying a can of blue paint with a hole punched in the bottom. Over many days, as he moved through the city, a continuous stream of paint dribbled onto the ground in a trail behind him. The line of blue paint made a map of his journey, a portrait of time. Alÿs's performance illustrates hyphal growth. Alÿs himself is the growing tip. The winding trail he leaves behind him is the body of the hypha. Growth happens at the tip; if one paused Alÿs as he walked around with his can of paint, the line would cease to grow. You can think of your life like this. The growing tip is the present moment—your lived experience of now—which gnaws into the future as it advances. The history of your life is the rest of the hypha, the blue lines that you've left in a tangled trail behind you. A mycelial network is a map of a fungus's recent history and is a helpful reminder that all life-forms are in fact *processes* not *things*. The "you" of five years ago was made from different stuff than the "you" of today. Nature is an event that never stops. As William Bateson, who coined the word *genetics*, observed, "We commonly think of animals and plants as matter, but they are really systems through which matter is continually passing." When we see an organism, from a fungus to a pine tree, we catch a single moment in its continual development.

Mycelium usually grows from hyphal tips, but not always. When hyphae felt together to make mushrooms, they rapidly inflate with water, which they must absorb from their surroundings—the reason why mushrooms tend to appear after rain. Mushroom growth can generate an explosive force. When a stinkhorn mushroom crunches through an asphalt road, it produces enough force to lift an object weighing 130 kilograms. In a popular fungal guidebook published in the 1860s, Mordecai Cooke reported that "some years ago the [English] town of Basingstoke was paved; and not many months afterward the pavement was observed to exhibit an unevenness which could not readily be accounted for. In a short time after, the mystery was explained, for some of the heaviest stones were completely lifted out of their beds by the growth of large toadstools beneath them. One of the stones measured twenty-two inches by twenty-one, and weighed eighty-three pounds.”

If I think about mycelial growth for more than a minute my mind starts to stretch.

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IN THE MID-1980S, the American musicologist Louis Sarno recorded the music of the Aka people living in the forests of the Central African Republic. One of these recordings is called “Women Gathering Mushrooms.” As they wander around collecting mushrooms, their steps tracing the underground form of a mycelial network, the women sing amid the sounds of the animals in the forest. Each woman sings a different melody; each voice tells a different musical story. Many melodies intertwine without ceasing to be many. Voices flow around other voices, twisting into and beside one another.

“Women Gathering Mushrooms” is an example of musical polyphony. Polyphony is singing more than one part, or telling more than one story, at the same time. Unlike the harmonies in a barbershop quartet, the voices of the women never weld into a unified front. No voice surrenders its individual identity. Nor does any one voice steal the show. There is no front woman, no soloist, no leader. If the recording was played to ten people and they were asked to sing the tune back, each would sing something different.

Mycelium is polyphony in bodily form. Each of the women’s voices is a hyphal tip, exploring a soundscape for itself. Although each is free to wander, their wanderings can’t be seen as separate from the others. There is no main voice. There is no lead tune. There is no central planning. Nonetheless, a form emerges.

Whenever I listen to “Women Gathering Mushrooms,” my ears find their way into the music by choosing a single voice and riding with it, as if I were in the forest and could walk up to one of the women and stand next to her. To follow more than one line at a time is hard. It is like trying to listen to many conversations at once without flicking from one to another. Several streams of consciousness have to commingle in the mind. My attention has to become less focused and more distributed. I fail every time, but when I soften my hearing, something else happens. The many songs coalesce to make one song that doesn't exist in any one of the voices alone. It is an emergent song that I can't find by unraveling the music into its separate strands.

Mycelium is what happens when fungal hyphae—streams of embodiment rather than streams of consciousness—commingle. However, as Alan Rayner, a mycologist specializing in mycelial development, reminded me, "Mycelium is not just amorphous cotton wool." Hyphae can come together to form elaborate structures.

When you look at mushrooms, you're looking at fruit. Imagine bunches of grapes growing out of the ground in their place. Then imagine the vine that produced them, twisting and branching below the surface of the soil. Grapes and woody grapevines are made of different types of cell. Cut up a mushroom and you'll see that it is made of the same type of cell as mycelium: hyphae.

Hyphae grow into other structures besides mushrooms. Many species of fungus form hollow cables of hyphae known as "cords" or "rhizomorphs." These range from slim filaments to strands several millimeters thick that can stretch for hundreds of meters. Given that individual hyphae are tubes, not threads—it is easy to forget about the fluid-filled space within the hyphae—cords and rhizomorphs are large pipes formed from many small tubes. They can conduct a flow thousands of times faster than through individual hyphae—nearly 1.5 meters per hour in one report—and allow mycelial networks to transport nutrients and water over large distances. Olsson told me about a forest in Sweden where he had observed a large *Armillaria* network that fruited over an area the size of two football fields. A small footbridge crossed a stream that flowed through the area. "I started looking more closely at the bridge," he remembered, "and saw that the fungus had started to wind its cords under the bridge. It was actually crossing the stream using the bridge." How fungi coordinate the growth of these structures remains a mystery.

Mushrooms, like mycelium, are made of hyphae.

Cords and rhizomorphs are a good reminder that mycelial networks are transport networks. Boddy's mycelial road map is another good illustration. Mushroom growth is another: To push their way through asphalt, a mushroom must inflate with water. For this to happen, water must travel rapidly through the network from one place to another and flow into a developing mushroom in a carefully directed pulse.

Over short distances, substances can be transported through mycelial networks on a network of microtubules—dynamic filaments of protein that behave like a cross between scaffolding and escalators. Transport using microtubule "motors" is energetically costly, however, and over larger distances the contents of hyphae travel on a river of cellular fluid. Both approaches allow rapid transport across mycelial networks. Efficient transport allows different parts of a mycelial network to engage in different activities. When the English country house Haddon Hall was being renovated, a fruiting body of the dry-rot fungus *Serpula* was found in a disused stone oven. Its mycelial connections wound back through eight meters of stonework to a rotting floor elsewhere in the building. The floor was where it fed, the oven was where it fruited.

The best way to appreciate flow within mycelium is to watch its contents shuttle around the network. In 2013, a group of researchers at the University of California at Los Angeles treated mycelium so that they could visualize cellular structures moving within the hyphae. Their videos show hordes of nuclei surging along. In some hyphae they travel faster than in others, in some they travel in different directions. Sometimes traffic jams form and nuclear traffic is rerouted on hyphal slip channels. Streams of nuclei merge with each other. Rhythmic pulses of nuclei—“nuclear comets”—rush along, branching at junctions and darting down side ducts. It is a scene of “nuclear anarchy,” as one of the researchers wryly observed.

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FLOW HELPS TO explain how traffic circulates within a mycelial network, but it can’t explain why fungi might grow in one direction rather than another. Hyphae are sensitive to stimuli, and at any one moment are confronted with a world of possibilities. Rather than extending in a straight line at a constant rate, hyphae steer themselves toward appealing prospects and away from unappealing ones. How?

In the 1950s, the Nobel Prize–winning biophysicist Max Delbrück became interested in sensory behavior. He chose as his model organism the fungus *Phycomyces blakesleeanus*. Delbrück was fascinated by *Phycomyces*’s remarkable perceptual abilities. Its fruiting structures—essentially giant vertical hyphae—have a sensitivity to light similar to that of the human eye and adapt to bright or low light as our eyes do. They can detect light at levels as low as that provided by a single star, and only become dazzled when exposed to full sunlight on a bright day. To provoke a response in a plant, one would have to expose it to light levels hundreds of times higher.

At the end of his career, Delbrück wrote that he was still convinced that *Phycomyces* was “the most intelligent” of the simpler multicellular organisms. Besides its exquisite sensitivity to touch—*Phycomyces* preferentially grows into wind at speeds as low as one centimeter per second, or 0.036 kilometers per hour—*Phycomyces* is able to detect the presence of nearby objects, a phenomenon known as the "avoidance response." Despite decades of painstaking investigation, the avoidance response remains an enigma. Objects within a few millimeters cause the fruiting body of *Phycomyces* to bend away without ever making contact. Regardless of the object—opaque or transparent, smooth or rough—*Phycomyces* starts to bend away after about two minutes. Electrostatic fields, humidity, mechanical cues, and temperature have all been ruled out. Some hypothesize that *Phycomyces* uses a volatile chemical signal that deflects around the obstacle with tiny air currents, but this is far from proven.

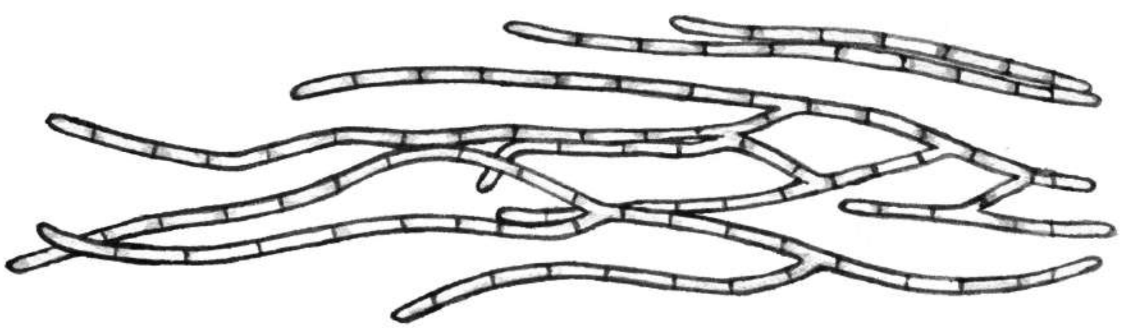
Although *Phycomyces* is an unusually sensitive species, most fungi are able to detect and respond to light (its direction, intensity, or color), temperature, moisture, nutrients, toxins, and electrical fields. Like plants, fungi can "see" color across the spectrum using receptors sensitive to blue light and red light—unlike plants, fungi also have opsins, the light-sensitive pigments present in the rods and cones of animal eyes. Hyphae can also sense the texture of surfaces; one study reports that young hyphae of the bean rust fungus can detect grooves half a micrometer deep in artificial surfaces, three times shallower than the gap between the laser tracks on a CD. When hyphae felt together to make mushrooms, they acquire an acute sensitivity to gravity. And as we've seen, fungi maintain countless channels of chemical communication with other organisms and with themselves: When they fuse or have sex, hyphae distinguish "self" from "other," and between different kinds of "other."

Fungal lives are lived in a flood of sensory information. And somehow, hyphae—piloted by their tips—are able to *integrate* these many data streams and determine a suitable trajectory for growth. Humans, like most animals, use brains to integrate sensory data and decide on the best course of action. Accordingly, we tend to look for particular places where integration might take place. We like a *where*, but with plants and fungi, asking "where" only gets us so far. There are different parts of a mycelial network or a plant, but they aren't unique. There are many of everything.

How, then, do sensory data streams come together within a mycelial network? How do brainless organisms link perception with action?

Plant scientists have wrestled with these questions for more than a century. In 1880, Charles Darwin and his son Francis published a book called *The Power of Movement in Plants*. In the final paragraph, they suggest that since root tips determine the trajectory for growth, it must be at the root tips that signals from different parts of the organism are integrated. Root tips, the Darwins write, act “like the brain of one of the lower animals…receiving impressions from the sense-organs, and directing the several movements.” The Darwins’ conjecture has come to be known as the “root-brain” hypothesis and is controversial, to put it mildly. This is not because anyone disputes their observations: It is clear that root tips do direct the movement of roots, just as growing tips direct the movement of shoots above ground. What divides plant scientists is the use of the word *brain*. For some, it is a proposition that can draw us toward a richer understanding of plant life. For others, it is preposterous to suggest that plants have anything even like a brain.

In some sense, the word *brain* is a distraction. The Darwins’ main point is that growing tips—which pilot roots and shoots—must be the place where information comes together to link perception and action, and determine a suitable course for growth. The same applies to fungal hyphae. Hyphal tips are the parts of the mycelium that grow, change direction, branch, and fuse. They are the part of the mycelium that do the most. And they are numerous. A given mycelial network might have anywhere between hundreds and billions of hyphal tips, all integrating and processing information on a massively parallel basis.



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HYPHAL TIPS MAY be the places where data streams come together to determine the speed and direction of growth, but how do tips in one part of the network "know" what tips are doing in other, more distant parts of the network? We stumble back into Olsson's conundrum. His bioluminescent *Panellus* cultures were able to coordinate their behavior over time periods too short to be caused by chemicals moving from A to B through the network. The mycelium of some fungal species grows into "fairy rings" that stretch across hundreds of meters, reach hundreds of years in age, and then somehow produce a circle of mushrooms in a synchronized flush. In Boddy's experiments with foraging mycelium, only one part of the network discovered the new block of wood, but the behavior of the entire mycelium changed, and changed rapidly. How are mycelial networks able to communicate with themselves? How does information travel across mycelial networks so quickly?

There are a number of possibilities. Some researchers suggest that mycelial networks might transmit developmental cues using changes in pressure or flow—because mycelium is a continuous hydraulic network like a car's braking system, a sudden change in pressure in one part could, in principle, be felt rapidly everywhere else. Some have observed that metabolic activity—such as the accumulation and release of compounds within hyphal compartments—can take place in regular pulses that could help to synchronize behavior across a network. Olsson, for his part, turned his attention to one of the few other options that remained: electricity.

It has long been known that animals use electrical impulses, or "action potentials," to communicate between different parts of their bodies. Neurons—the long, electrically excitable nerve cells that coordinate animal behavior—have their own field of study: neuroscience. Although electrical signaling is normally thought of as an animal talent, animals aren't alone in producing action potentials. Plants and algae produce them, and it has been known since the 1970s that some types of fungi do also. Bacteria, too, are electrically excitable. "Cable bacteria" form long electrically conductive filaments, known as nanowires. And it has been known since 2015 that bacterial colonies can coordinate their activity using action potential–like waves of electrical activity. Nonetheless, few mycologists imagined that it could play an important role in fungal lives.

In the mid-1990s in Olsson's department at Lund University in Sweden, there was a research group working on insect neurobiology. In their experiments, they measured the activity of neurons by inserting fine glass microelectrodes into moth brains. Olsson approached them and asked if he could use their rig to ask a simple question: What would happen if he replaced the moth brains with fungal mycelium? The neuroscientists were intrigued. In principle, fungal hyphae should be well-adapted to conduct electrical impulses. They are coated with proteins that insulate them, which would allow waves of electrical activity to travel long distances without dissipating—animal nerve cells have an analogous insulating sheath. Moreover, the cells in a mycelium are continuous with one another, possibly allowing impulses initiated in one part of the network to reach another part without interruption.

Olsson chose the species of fungus carefully. He surmised that if electrical communication systems did exist in fungi, it would be easier to detect in species with a greater need for communication over long distances. Just to be safe, he chose a honey fungus, or *Armillaria*—the species that forms the record-holding mycelial networks that stretch over kilometers and reach thousands of years in age.

When Olsson inserted the microelectrodes into *Armillaria*'s hyphal strands, he detected regular action potential–like impulses, firing at a rate very close to that of animals' sensory neurons—around four impulses per second, which traveled along hyphae at a speed of at least half a millimeter per second, some ten times faster than the fastest rate of fluid flow measured in a fungal hypha. This caught his attention, but in itself it didn't suggest that the impulses formed the basis of a rapid signaling system. Electrical activity can only play a role in fungal communication if it is sensitive to stimulation. Olsson decided to measure the response of the fungus to blocks of wood, which is food for this species.

Olsson set up the rig and placed a block of wood onto the mycelium several centimeters from the electrodes. What he found was extraordinary. When the wood came into contact with the mycelium, the firing rate of the impulses doubled. When he removed the block of wood, the firing rate returned to normal. To make sure that the fungi weren't responding to the weight of the wooden block, he placed an inedible plastic block of the same size and weight onto the mycelium. The fungus didn't respond.

Olsson went on to test a range of other species of fungus, including a mycorrhizal fungus growing on the root system of a plant, *Pleurotus* (or oyster mushroom mycelium), and *Serpula* (the dry rot found fruiting in the oven at Haddon Hall). They all generated action potential–like impulses and were sensitive to a range of different stimuli. Olsson hypothesized that electrical signaling was a realistic way for a wide variety of fungi to send messages between different parts of themselves, messages that conveyed information about "food sources, injury, local conditions within the fungus, or the presence of other individuals around it."

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MANY OF THE neurobiologists Olsson was working with became excited that mycelial networks could be behaving like brains. "It was the first reaction from all the insect people," Olsson recalled. "They were thinking of these big mycelial networks in the forest sending electric signals around themselves. They imagined that maybe they were just big brains lying there." I admit that I hadn't been able to ignore the superficial resemblance either. Olsson's findings suggested that mycelium might form fantastically complex networks of electrically excitable cells. Brains, too, are fantastically complex networks of electrically excitable cells.

"I don't think they're brains," Olsson explained to me. "I had to hold back the brain concept. As soon as one says it, people start thinking of brains like ours where we have language and process thoughts to make decisions." His caution is well-placed. *Brain* is a trigger word, burdened with concepts that spend most of their time in the animal world. "When we say 'brain,'" Olsson continued, "all associations are with animal brains." Besides, as he pointed out, brains behave like brains because of the way they're built. The architecture of animal brains is very different from that of fungal networks. In animal brains, neurons connect with other neurons at junctions called synapses. At synapses, signals can combine with other signals. Neurotransmitter molecules pass across synapses and allow different neurons to behave in different ways—some excite other neurons, some inhibit them. Mycelial networks don't share any of these features.

But if fungi did use waves of electrical activity to transmit signals around a network, wouldn't we think of mycelium as at least a brain-*like* phenomenon? In Olsson's view, there could be other ways to regulate electrical impulses in mycelial networks to create "brain-like circuits, gates, and oscillators." In some fungi, hyphae are divided into compartments by pores, which can be sensitively regulated. Opening or closing a pore changes the strength of the signal that passes from one compartment to another, whether chemical, pressure, or electrical. If sudden changes in the electrical charge within a hyphal compartment could open or close a pore, Olsson mused, a burst of impulses could change the way subsequent signals passed along the hypha and form a simple learning loop. What's more, hyphae branch. If two impulses converged on one spot, they would both influence pore conductivity, integrating signals from different branches. "You do not need much knowledge of how computers work to realize that such systems can create decision gates," Olsson told me. "If you combine these systems in a flexible and adaptable network we have the possibility for 'a brain' that could learn and remember." He held the word *brain* at a safe distance, clamped in the forceps of quotation marks to emphasize that a metaphor was in play.

That fungi could use electrical signaling as a basis for rapid communication has not been lost on Andrew Adamatzky, the director of the Unconventional Computing Laboratory. In 2018, he inserted electrodes into whole oyster mushrooms sprouting in clusters from blocks of mycelium and detected spontaneous waves of electrical activity. When he held a flame up to a mushroom, different mushrooms within the cluster responded with a sharp electrical spike. Shortly afterward, he published a paper called "Towards fungal computer." In it, he proposed that mycelial networks "compute" information encoded in spikes of electrical activity. If we knew how a mycelial network would respond to a given stimulus, Adamatzky argues, we could treat it like a living circuit board. By stimulating the mycelium—for example, using a flame or a chemical—we could input data into the fungal computer.

A fungal computer may sound fantastical, but biocomputing is a fast-growing field. Adamatzky has spent years developing ways to use slime molds as sensors and computers. These prototype biocomputers use slime molds to solve a range of geometrical problems. The slime mold networks can be modified—for instance, by cutting a connection—to alter the set of "logical functions" implemented by the network. Adamatzky's idea of a "fungal computer" is just an application of slime-mold computing to another type of network-based organism.

As Adamatzky observes, the mycelial networks of some species of fungus are more convenient for computing than slime molds. They form longer-lived networks and don't morph into new shapes quite so quickly. They are also larger, with more junctions between hyphae. It is at these junctions—what Olsson described as "decision gates," and what Adamatzky describes as "elementary processors"—that signals from different branches of the network would interact and combine. Adamatzky estimates that a network of honey fungus stretching over fifteen hectares would have nearly a trillion such processing units.

For Adamatzky, the point of fungal computers is not to replace silicon chips. Fungal reactions are too slow for that. Rather, he thinks humans could use mycelium growing in an ecosystem as a "large-scale environmental sensor." Fungal networks, he reasons, are monitoring a large number of data streams as part of their everyday existence. If we could plug into mycelial networks and interpret the signals they use to process information, we could learn more about what was happening in an ecosystem. Fungi could report changes in soil quality, water purity, pollution, or any other features of the environment that they are sensitive to.

We're some way off. Computing with living network-based organisms is in its infancy and many questions remain unanswered. Olsson and Adamatzky have shown that mycelium can be electrically sensitive, but they haven't shown that electrical impulses can link a stimulus to a response. It is as if you had stuck a pin in your toe, detected the nerve impulse that traveled through your body, but hadn't been able to measure your reaction to the pain.

This is a challenge for the future. In the twenty-three years between Olsson's study on mycelium and Adamatzky's study on oyster mushrooms, no further research was conducted on electrical signaling in fungi. If he had the resources to pursue this line of inquiry, Olsson told me that he would try to demonstrate a clear physiological response to changes in electrical activity and decode the patterns of electrical impulses. His dream is to “hook up a fungus with a computer and communicate with it,” to use electrical signals to get the fungus to change its behavior. “All sorts of weird and wonderful experiments could be done if this turns out to be right.”

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THESE STUDIES RAISE a storm of questions. Are network-based life-forms like fungi or slime molds capable of a form of cognition? Can we think of their behavior as intelligent? If other organisms’ intelligence didn’t look like ours, then how might it appear? Would we even notice it?

Among biologists, opinion is divided. Traditionally, intelligence and cognition have been defined in human terms as something that requires at least a brain and, more usually, a mind. Cognitive science emerged from the study of humans and so naturally placed the human mind at the center of its inquiry. Without a mind, the classical examples of cognitive processes—language, logic, reasoning, recognizing oneself in a mirror—seem impossible. All require high-level mental functioning. But how we define intelligence and cognition is a question of taste. For many, the brain-centric view is too limited. The idea that a neat line can be drawn that separates nonhumans from humans with “real minds” and “real comprehension” has been curtly dismissed by the philosopher Daniel Dennett as an “archaic myth.” Brains didn’t evolve their tricks from scratch, and many of their characteristics reflect more ancient processes that existed long before recognizable brains arose.

Charles Darwin, writing in 1871, took a pragmatic line. “Intelligence is based on how efficient a species becomes at doing the things they need to survive.” It is a perspective that has been echoed by many contemporary biologists and philosophers. The Latin root of the word *intelligence* means “to choose between.” Many types of brainless organisms—plants, fungi, and slime molds included—respond to their environments in flexible ways, solve problems, and make decisions between alternative courses of action. Complex information processing is evidently not restricted to the inner workings of brains. Some use the term “swarm intelligence” to describe the problem-solving behavior of brainless systems. Others suggest that the behavior of these network-based life-forms can be thought of as arising from “minimal” or “basal” cognition, and argue that the question we should ask is not whether an organism has cognition or not. Rather, we should assess the *degree* to which an organism might be cognizant. In all these views, intelligent behaviors can arise without brains. A dynamic and responsive network is all that’s needed.

The brain has long been thought of as a dynamic network. In 1940, the Nobel Prize–winning neurobiologist Charles Sherrington described the human brain as “an enchanted loom where millions of flashing shuttles weave a dissolving pattern.” Today, “network neuroscience” is the name given to the discipline that attempts to understand how the brain’s activity emerges from the interlinked activity of millions of neurons. A single neuronal circuit within one’s brain can’t give rise to intelligent behavior, just as the behavior of a single termite can’t give rise to the intricate architecture of a termite mound. No single neuronal circuit “knows” what’s going on any more than a single termite “knows” the structure of the mound, but large numbers of neurons can build a network from which surprising phenomena can emerge. In this view, complex behaviors—including minds and the nuanced textures of lived, conscious experience—arise out of complex networks of neurons flexibly remodeling themselves.

Brains are just one such network, one way of processing information. Even in animals, there is a lot that can take place without them. Researchers at Tufts University have illustrated this in striking experiments using flatworms. Flatworms are well-studied model organisms because of their ability to regenerate. If the head of a flatworm is cut off, it sprouts another head, brain and all. Flatworms can also be trained. The researchers wondered whether, if they trained a flatworm to remember features of its environment and then cut off its head, it would retain the memory when it has grown a new head and brain. Remarkably, the answer is yes. The flatworms’ memory appeared to reside in a part of their body outside the brain. These experiments suggest that even within the body of braindependent animals, the flexible networks that underpin complex behaviors need not be limited to a small region inside the head. There are other examples. Most nerves in octopuses are not found in the brain, for instance, but are distributed throughout their bodies. A large number are found in the tentacles, which can explore and taste their surroundings without involving the brain. Even when amputated, tentacles are able to reach and grasp.

Many types of organisms, then, have evolved flexible networks to help solve the problems that life presents. Mycelial organisms appear to be some of the first to do so. In 2017, researchers at the Swedish Royal Museum of Natural History published a report in which they describe fossilized mycelium preserved in the fractures of ancient lava flows. The fossils show branching filaments that "touch and entangle each other." The "tangled network" they form, the dimensions of the hyphae, the dimensions of spore-like structures, and the pattern of its growth all closely resemble modern-day fungal mycelium. It is an extraordinary discovery because the fossils date from 2.4 billion years ago, more than a billion years before fungi were thought to have branched off the tree of life. There is no way to identify the organism with certainty, but whether or not it was a true fungus, it clearly had a mycelial habit. It is a finding that makes mycelium one of the earliest known gestures toward complex multicellular life, an original tangle, one of the first living networks. Remarkably unchanged, mycelium has persisted for more than half of the four billion years of life's history, through countless cataclysms and catastrophic global transformations.

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BARBARA MCCLINTOCK, WHO won the Nobel Prize for her work on maize genetics, described plants as extraordinary "beyond our wildest expectations." Not because they have found ways to do what humans can do but because a life lived rooted to one spot has coaxed them to evolve countless "ingenious mechanisms" to deal with challenges that animals might avoid by simply running away. We could say the same of fungi. Mycelium is one such ingenious solution, a brilliant reply to some of life's most basic challenges. Mycelial fungi don't do as we do, and contain flexible networks that ceaselessly remodel themselves. They *are* flexible networks that ceaselessly remodel themselves.

McClintock emphasizes how important it is to acquire “a feeling for the organism,” to develop the patience to “hear what the material has to say to you.” When it comes to fungi, do we really stand a chance? Mycelial lives are so *other*, their possibilities so strange. But perhaps they aren’t quite so remote as they seem at first glance. Many traditional cultures understand life to be an entangled whole. Today, the idea that all things are interconnected has been so well-used that it has collapsed into a cliché. The idea of the “web of life” underpins modern scientific conceptions of nature; the school of “systems theory,” which arose during the twentieth century, understands all systems—from traffic flows to governments to ecosystems—to be dynamic networks of interaction; the field of “artificial intelligence” solves problems using artificial neural networks; many aspects of human life are continuous with the digital networks of the Internet; network neuroscience invites us to understand *ourselves* as dynamic networks. Like a well-exercised muscle, “network” has hypertrophied into a master concept. It is hard to think of a subject that networks aren’t used to make sense of.

Yet we still struggle to make sense of mycelium. I asked Boddy what aspects of mycelial lives remain most mysterious. “Ah…that’s a good question.” She faltered. “I really don’t know. There are just *so many things*. How do mycelial fungi work *as networks*? How do they sense their environment? How do they send messages back to other parts of themselves? How are those signals then integrated? These are all huge questions which hardly anyone seems to be thinking about. Yet understanding these things is crucial to understanding how fungi do almost everything that they do. We have techniques to do this work, but who is looking at basic fungal biology? Not many people. I think it’s a very worrying situation. We haven’t put together many of the things we’ve found into an overall understanding.” She laughed. “The field is ripe for picking! But I don’t think there are many people out there doing the picking.”

In 1845, Alexander von Humboldt observed that “Each step that we make in the more intimate knowledge of nature leads us to the entrance of new labyrinths.” Polyphonic songs like “Women Gathering Mushrooms” emerge from the entangling of voices; mycelium emerges from the entangling of hyphae. A sophisticated understanding of mycelium is yet to emerge. We are standing at the entrance to one of the oldest of life's labyrinths.