ANNALS OF TECHNOLOGY

THE SECRETS OF THE WOOD WIDE WEB

In London's Epping Forest, a scientist named Merlin eavesdrops on trees' underground conversations.

By Robert Macfarlane

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Epping Forest is a heavily regulated place. First designated as a royal hunting ground by Henry II in the twelfth century, with severe penalties imposed on commoners for poaching, it has since 1878 been managed by the City of London Corporation, which governs behavior within its bounds using forty-eight bylaws. The forest is today almost completely contained within the M25, the notorious orbital motorway that encircles outer London. Minor roads crisscross it, and it is rarely more than four kilometres wide. Several of its hundred or so lakes and ponds are former blast holes of the V1 "doodlebug" rockets flung at London in 1944. Yet the miraculous fact of Epping's existence remains: almost six thousand acres of trees, heath, pasture, and waterways, just outside the city limits, its grassland still grazed by the cattle of local commoners, and adders still basking in its glades. Despite its mixed-amenity use—from golf to mountain biking—it retains a greenwood magic.

Earlier this summer I spent two days there, wandering and talking with a young plant scientist named Merlin Sheldrake. Sheldrake is an expert in mycorrhizal fungi, and as such he is part of a research revolution that is changing the way we think about forests. For centuries, fungi were widely held to be harmful to plants, parasites that cause disease and dysfunction. More recently, it has become understood that certain kinds of common fungi exist in subtle symbiosis with plants, bringing about not infection but connection. These fungi send out gossamer-fine fungal tubes called hyphae, which infiltrate the soil and weave into the tips of plant roots at a cellular level. Roots and fungi combine to form what is called a mycorrhiza: itself a growing-together of the Greek words for fungus (*mykós*) and root (*riza*). In this way, individual plants are joined to one another by an underground hyphal network: a dazzlingly complex and collaborative structure that has become known as the Wood Wide Web.

The relationship between these mycorrhizal fungi and the plants they connect is now known to be ancient (around four hundred and fifty million years old) and largely one of mutualism—a subset of symbiosis in which both organisms benefit from their association. In the case of the mycorrhizae, the fungi siphon off food from the trees, taking some of the carbon-rich sugar that they produce during photosynthesis. The plants, in turn, obtain nutrients such as phosphorus and nitrogen that the fungi have acquired from the soil, by means of enzymes that the trees do not possess.

The implications of the Wood Wide Web far exceed this basic exchange of goods between plant and fungi, however. The fungal network also allows plants to distribute resources—sugar, nitrogen, and phosphorus—between one another. A dying tree might divest itself of its resources to the benefit of the community, for example, or a young seedling in a heavily shaded understory might be supported with extra resources by its stronger neighbors. Even more remarkably, the network also allows plants to send one another warnings. A plant under attack from aphids can indicate to a nearby plant that it should raise its defensive response before the aphids reach it. It has been known for some time that plants communicate above ground in comparable ways, by means of airborne hormones. But such warnings are more precise in terms of source and recipient when sent by means of the myco-net.

The revelation of the Wood Wide Web's existence, and the increased understanding of its functions, raises big questions—about where species begin and end; about whether a forest might be better imagined as a single superorganism, rather than a grouping of independent individualistic ones; and about what trading, sharing, or even friendship might mean among plants. "Whenever I need to explain my research to someone quickly, I just tell them I work on the social networks of plants," Sheldrake told me.

Sheldrake is twenty-eight years old and tall, with a tight head of dark curls. When we met, he was wearing a blue paisley-pattern neckerchief, a collarless woollen jacket, and a khaki canvas rucksack with gleaming brass buckles. He resembled a Victorian plant hunter, ready for the jungle. In addition to his academic pursuits, Sheldrake plays accordion in a band called the Gentle Mystics, whose tracks include a trance epic called "Mushroom 30,000," and whose musical style might best be described as myco-klezmer-hip-hop-electro-burlesque. Once heard, bewildered. Twice heard, hooked.

As an undergraduate studying natural sciences at Cambridge, in the late aughts, Sheldrake read the 1988 paper "Mycorrhizal Links Between Plants: Their Functioning and Ecological Significance," by the plant scientist E. I. Newman, in which Newman argued boldly for the existence of a "mycelial network" linking plants. "If this phenomenon is widespread," Newman wrote, "it could have profound implications for the functioning of ecosystems."

Those implications fascinated Sheldrake. He had long loved fungi, which seemed to him possessed of superpowers. He knew that they could turn rocks to rubble, move with eerie swiftness both above ground and under it, reproduce horizontally, and digest food outside their bodies via excreted enzymes. He was aware that their toxins could kill people, and that their psychoactive chemicals could induce hallucinogenic states. After reading Newman's paper, he understood that fungi could also allow plants to communicate with one another.

"All of these trees will have mycorrhizal fungi growing into their roots," Sheldrake said, gesturing at the beech and hornbeam through which we were walking. "You could imagine the fungi themselves as forming a massive underground tree, or as a cobweb of fine filaments, acting as a sort of prosthesis to the trees, a further root system, extending outwards into the soil, acquiring nutrients and floating them back to the plants, as the plants fix carbon in their leaves and send sugar to their roots, and out into the fungi. And this is all happening right under our feet."

We reached a broad clearing in which hundreds of bright-green beech seedlings were flourishing, each a few centimetres high, drawn by the ready light. Sheldrake knelt down and brushed away leaves to reveal a patch of soil the size of a dinner plate. He pinched up some of the earth and rubbed it between his fingers: rich, dark humus. "Soil is fantastically difficult stuff to work with experimentally, and the hyphae are on the whole too thin to see," he said. "You can put rhizotrons into the ground to look at root growth—but those don't really give you the fungi because they are too fine. You can do below-ground laser scanning, but again that is too crude for the fungal networks."

Gleaming yellow-brown spiders and bronze beetles battled over the leaves. “Hyphae will be growing around in the decomposing matter of this half-rotting leaf, those rotting logs, and those rotting twigs, and then you’ll have the mycorrhizal fungi whose hyphae grow into hotspots,” Sheldrake said, pointing around the glade. In addition to penetrating the tree roots, the hyphae also interpenetrate each other—mycorrhizal fungi on the whole don’t have divisions between their cells. “This interpenetration permits the wildly promiscuous horizontal transfer of genetic material: fungi don’t have to have sex to pass things on,” Sheldrake explained. I tried to imagine the soil as transparent, such that I could peer down into this subterranean infrastructure, those spectral fungal skeins suspended between the tapering tree roots, creating a network at least as intricate as the cables and optical fibres beneath our cities. I once heard the writer China Miéville use a particular phrase for the realm of fungi: “The kingdom of the gray.” It captured their otherness: the challenges fungi issued to our usual models of time, space, scale, and species. “You look at the network,” Sheldrake said. “And then it starts to look back at you.”

The relationship between mycorrhizal fungi and the plants they connect is now known to be ancient—around four hundred and fifty million years old. *Illustration by Enzo Pérès-Labourdette* Illustration by Enzo Pérès-Labourdette

After two hours we ran out of forest, rebounded off the M25, hopped a barbed-wire fence, and came to rest in a field that looked as if it belonged to a private landowner. We weren't lost, exactly, but we did need to know where the forest widened again. I pulled up the hybrid map of Epping on my phone, and a blue dot pulsed our location. The forest flared green to the southwest, so that was where we headed, crossing a busy road and then pushing deeper into the trees until we could hardly hear car noise.

When Sheldrake began his Ph.D., in 2011, there was no single figure at Cambridge with an expertise in symbiosis and mycorrhizae, so he contacted researchers he admired at other institutions, until he had established what he calls a "network of subject godparents—some in Sweden, in Germany, in Panama, in America, in England, where I was beholden to none, but part of their extended families." In the second year of his doctorate, Sheldrake went to the Central American jungle for field work: to Barro Colorado Island, located in the man-made Gatun Lake, in the Panama Canal. There he joined a community of field scientists, overseen by a grizzled American evolutionary biologist named Egbert Giles Leigh, Jr.

Some of the science undertaken on the island was what might be called methodologically high-risk. One young American scientist, researching what Sheldrake called the "drunken-monkey hypothesis," was attempting to collect monkey urine, after the monkeys had feasted on fermenting fruit, and assess it for intoxication levels. Sheldrake faced his own research frustrations. Much of his early work involved him taking spore samples back to the lab for scrutiny, and he became uncomfortable with how so much of what he dealt with in the lab was "absolutely dead, boiled, fixed, embalmed." He longed for more direct contact with the fungi he was studying. One afternoon, he was examining mycorrhizal spores under a microscope, when it occurred to him that they looked just like caviar. After hours of cleaning and sifting, he had enough to pile, with a pair of tweezers, onto a tiny fragment of biscuit, which he then ate. "They're really good for you, spores, full of all these lipids," he said. On occasion he has cut them into lines and snorted them.

During his second season on the island, Sheldrake became interested in a type of plants called mycoheterotrophs, or "mycohets" for short. Mycohets are plants that lack chlorophyll, and thus are unable to photosynthesize, making them entirely reliant on the fungal network for their provision of carbon. "These little green-less plants plug into the network, and somehow derive everything from it without paying anything back, at least in the usual coin," Sheldrake said. "They don't play by the normal rules of symbiosis, but we can't prove they're parasites." Sheldrake focussed on a genus of mycohets called *Voyria*, part of the gentian family, the flowers of which studded the jungle floor on Barro Colorado Island like pale purple stars.

A central debate over the Wood Wide Web concerns the language used to describe the transactions it enables, which suggest two competing visions of the network: the socialist forest, in which trees act as caregivers to one another, with the well-off supporting the needy, and the capitalist forest, in which all entities are acting out of self-interest within a competitive system. Sheldrake was especially exasperated by what he called the "super-neoliberal capitalist" discourse of the biological free market. One of the reasons Sheldrake loved the *Voyria*, he explained, is that they were harder to understand, mysterious: "They are the hackers of the Wood Wide Web."

Working with local field assistants on the island —"the best botanists ever"— Sheldrake carried out a painstaking census of the soil in a series of plots, sequencing the DNA of hundreds of root samples taken both from green plants and the *Voyria*. This allowed him to determine which species of fungi were connecting which plants, and thereby to make an unprecedentedly detailed map of the jungle's social network. Sheldrake got out his phone and pulled up an image of the map on his screen. The intricacy of relation it represented reminded me of attempts I had seen to map the global Internet: a firework display of meshing lines and colors.

We stopped to eat in a dry part of the forest, on rising ground amid old pines. Sheldrake had brought two mangoes and a spinach tart. He drank beer, I drank water, and the pine roots snaked and interlaced around us. He told me about the home laboratory he runs on his kitchen table, and the microbrewery he runs in his garden shed. He has brewed mead from honey, as well as cider from the apples of Newton's apple tree, at Trinity College, Cambridge (batch name: Gravity), and from the apples of Darwin's orchard at Down House (batch name: Evolution).

Later in the day we came to a lake, where a hard-packed mud bank sloped down into shallow water. Carp burped in the shadows. Moorhen bickered. The lake bed belched gas bubbles. Sheldrake and I sat facing the setting sun, and he explained how, for each formal scientific paper he published about mycorrhizae, he planned also to publish the paper's "dark twin," in which he would describe the "messy network of crazy things that underlies every piece of cool, clean science, but that you aren't usually allowed to see—the fortunate accidents of field work, the tangential serendipitous observation that sets off a thought train, the boredom, the chance encounters." Two dog-walkers interrupted our conversation, looking hopeful. "Do you know where the visitors' center is?" one asked. "We're lost." "No, we're lost, too," I said, happily. We traded best guesses, exchanging what little information we had, and they wandered off.

Robert Macfarlane is a fellow of Emmanuel College, Cambridge.

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