VINTAGE

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About the Author

Merlin Sheldrake is a biologist and a writer. He received a Ph.D. in Tropical Ecology from Cambridge University for his work on underground fungal networks in tropical forests in Panama, where he was a predoctoral research fellow of the Smithsonian Tropical Research Institute. He is a musician and keen fermenter. *Entangled Life* is his first book.

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With gratitude to the fungi from which I have learned

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

Nicholas Humphrey, author of *Soul Dust*

‘Unputdownable, this extraordinary work, at once rigorously scientific and boldly imaginative, raises fundamental questions about the many natures of life on Earth’

Nick Jardine, University of Cambridge

‘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’

J. H. Prynne

‘A remarkable book that manages to be at once scholarly, visionary and a deeply engaging and enjoyable read. It provides a new and penetrating analysis that will be a greatly enriching read for all students of the living world’

Ian Henderson, University of Cambridge

‘In his remarkable first book, Sheldrake takes us on a host of profoundly eye-opening journeys into the astonishing worlds of the fungi. A masterpiece’

Stephan Harding, Schumacher College

‘A triumph and a thing of vast beauty’

Tom Hodgkinson, *The Idler*

‘This engaging book shines light on the hidden fungal connections that link plants, trees and us. Sheldrake is a rare scientist who is not afraid to speculate about the truly profound implications of his work. A very good read’

Andrew Weil, author of *True Food*

Prologue

I looked up towards the top of the tree. Ferns and orchids sprouted from its trunk, which vanished into a tangle of lianas in the canopy. High above me, a toucan flapped off its perch with a croak, and a troupe of howler monkeys worked themselves into a slow roar. The rain had only just stopped, and the leaves above me shed heavy drops of water in sudden showers. A low mist hung over the ground.

The tree's roots wound outwards from the base of its trunk, soon vanishing into the thick drifts of fallen leaves that covered the floor of the jungle. I used a stick to tap the ground for snakes. A tarantula scuttled off, and I knelt, feeling my way down the tree's trunk and along one of its roots into a mass of spongy debris where the finer roots matted into a thick red and brown tangle. A rich smell drifted upwards. Termites clambered through the labyrinth, and a millipede coiled up, playing dead. My root vanished into the ground, and with a trowel I cleared the area around the spot. I used my hands and a spoon to loosen the top layer of earth, and dug as gently as I could, slowly uncovering it as it ranged out from the tree and twisted along just below the surface of the soil.

After an hour, I had travelled about a metre. My root was now thinner than string and had started to proliferate wildly. It was hard to keep track of as it knotted with its neighbours, so I lay down on my stomach and lowered my face into the shallow trench I had made. Some roots smell sharp and nutty and others woody and bitter, but the roots of my tree had a spicy resinous kick when I scratched them with a fingernail. For several hours I inched along the ground, scratching and sniffing every few centimetres to make sure I hadn't lost the thread.

As the day went on, more filaments sprang out from the root I'd uncovered and I chose a few of them to follow all the way to the tips, where they burrowed into fragments of rotting leaf or twig. I dipped the ends in a vial of water to wash off the mud and looked at them through a loupe. The rootlets branched like a small tree and their surface was covered with a filmy layer which appeared fresh and sticky. It was these delicate structures I wanted to examine. From these roots, a fungal network laced out into the soil and around the roots of nearby trees. Without this fungal web my tree would not exist. Without similar fungal webs no plant would exist anywhere. All life on land, including my own, depended on these networks. I tugged lightly on my root and felt the ground move.

Introduction

What Is It Like To Be A Fungus?

> There are moments in moist love when heaven is jealous of
> what we on Earth can do.
>
> Hafiz

Fungi are everywhere but they are easy to miss. They are inside you and around you. They sustain you and all that you depend on. As you read these words, fungi are changing the way that life happens, as they have done for more than a billion years. They are eating rock, making soil, digesting pollutants, nourishing and killing plants, surviving in space, inducing visions, producing food, making medicines, manipulating animal behaviour and influencing the composition of the Earth's atmosphere. Fungi provide a key to understanding the planet on which we live, and the ways we think, feel and behave. Yet they live their lives largely hidden from view, and more than 90 per cent of their species remain undocumented. The more we learn about fungi, the less makes sense without them.

Fungi make up one of life's kingdoms – as broad and busy a category as 'animals' or 'plants'. Microscopic yeasts are fungi, as are the sprawling networks of honey fungi, or *Armillaria*, which are among the largest organisms in the world. The current record holder, in Oregon, weighs hundreds of tonnes, spills across 10 square kilometres, and is somewhere between 2,000 and 8,000 years old. There are probably many larger, older specimens that remain undiscovered.[1]

Many of the most dramatic events on Earth have been – and continue to be – a result of fungal activity. Plants only made it out of the water around 500 million years ago because of their collaboration with fungi, which served as their root systems for tens of million years until plants could evolve their own. Today, over 90 per cent of plants depend on mycorrhizal fungi – from the Greek words for fungus (*mykes*) and root (*rhiza*) – which can link trees in shared networks sometimes referred to as the 'Wood Wide Web'. This ancient association gave rise to all recognisable life on land, the future of which depends on the continued ability of plants and fungi to form healthy relationships.

Plants may have greened the planet, but if we could cast our eyes back to the Devonian period, 400 million years ago, we'd be struck by another life form: *Prototaxites*. These living spires were scattered across the landscape. Many were taller than a two-storey building. Nothing else got anywhere close to this size: plants existed but were no more than a metre tall, and no animal with a backbone had yet moved out of the water. Small insects made their homes in the giant trunks, chewing out rooms and corridors. This enigmatic group of organisms – thought to have been enormous fungi – were the largest living structures on dry land for at least 40 million years, twenty times longer than the genus *Homo* has existed.[2]

To this day, new ecosystems on land are founded by fungi. When volcanic islands are made or glaciers retreat to reveal bare rock, lichens (pronounced *LY-kens*) – a union of fungi and algae or bacteria – are the first organisms to establish themselves, and to make the soil in which plants subsequently take root. In well-developed ecosystems soil would be rapidly sluiced off by rain were it not for the dense mesh of fungal tissue that holds it together. From deep sediments on the sea floor, to the surface of deserts, to frozen valleys in Antarctica, to our guts and orifices, there are few pockets of the globe where fungi can't be found. Tens to hundreds of species can exist in the leaves and stems of a single plant. These fungi weave themselves through the gaps between plant cells in an intimate brocade and help to defend plants against disease. No plant grown under natural conditions has been found without these fungi; they are as much a part of planthood as leaves or roots.[3]

The ability of fungi to prosper in such a variety of habitats depends on their diverse metabolic abilities. Metabolism is the art of chemical transformation. Fungi are metabolic wizards and can explore, scavenge and salvage ingeniously, their abilities rivalled only by bacteria. Using cocktails of potent enzymes and acids, fungi can break down some of the most stubborn substances on the planet, from lignin, wood's toughest component, to rock, crude oil, polyurethane plastics and the explosive TNT. Few environments are too extreme. A species isolated from mining waste is one of the most radiation-resistant organisms ever discovered, and may help to clean up nuclear waste sites. The blasted nuclear reactor at Chernobyl is home to a large population of such fungi. A number of these radio-tolerant species even grow towards radioactive 'hot' particles, and appear to be able to harness radiation as a source of energy, as plants use the energy in sunlight.[4]

Mushrooms dominate the popular fungal imagination, but just as the fruits of plants are one part of a much larger structure that includes branches and roots, so mushrooms are only the fruiting bodies of fungi, the place where spores are produced. Fungi use spores like plants use seeds: to disperse themselves. Mushrooms are a fungus's way to entreat the more-than-fungal world, from wind to squirrel, to assist with the dispersal of spores, or prevent it from interfering with this process. They are the parts of fungi made visible, pungent, covetable, delicious, poisonous. However, mushrooms are only one approach among many: the overwhelming majority of fungal species release spores without producing mushrooms at all.

We all live and breathe fungi, thanks to the prolific abilities of fungal fruiting bodies to disperse spores. Some species discharge spores explosively, which accelerate 10,000 times faster than a Space Shuttle directly after launch, reaching speeds of up to a hundred kilometres per hour – some of the quickest movements achieved by any living organism. Other species of fungi create their own microclimates: spores are carried upwards by a current of wind generated by mushrooms as water evaporates from their gills. Fungi produce around fifty megatonnes of spores each year – equivalent to the weight of 500,000 blue whales – making them the largest source of living particles in the air. Spores are found in clouds and influence the weather by triggering the formation of the water droplets that form rain, and ice crystals that form snow, sleet and hail.[5]

Spores

Some fungi, like the yeasts that ferment sugar into alcohol and cause bread to rise, consist of single cells that multiply by budding into two. However, most fungi form networks of many cells known as hyphae (pronounced *HY-fee*): fine tubular structures that branch, fuse and tangle into the anarchic filigree of mycelium. Mycelium describes the most common of fungal habits, better thought of not as a thing, but as a process – an exploratory, irregular tendency. Water and nutrients flow through ecosystems within mycelial networks. The mycelium of some fungal species is electrically excitable and conducts waves of electrical activity along hyphae, analogous to the electrical impulses in animal nerve cells.[6]

Mycelium

Hyphae make mycelium, but they also make more specialised structures. Fruiting bodies, such as mushrooms, arise from the felting together of hyphal strands. These organs can perform many feats besides expelling spores. Some, like truffles, produce aromas that have made them among the most expensive foods in the world. Others, like shaggy ink cap mushrooms (*Coprinus comatus*), can push their way through asphalt and lift heavy paving stones, although they are not themselves a tough material. Pick an ink cap and you can fry it up and eat it. Leave it in a jar, and its bright white flesh will deliquesce into a pitch-black ink over the course of a few days (the illustrations in this book were drawn with *Coprinus* ink).[7]

Shaggy ink cap mushrooms, *Coprinus comatus*, drawn with ink made from shaggy ink cap mushrooms

Their metabolic ingenuity allows fungi to forge a wide variety of relationships. Whether in their roots or shoots, plants have relied on fungi for nutrition and defence for as long as there have been plants. Animals, too, depend on fungi. After humans, the animals that form some of the largest and most complex societies on Earth are leafcutter ants. Colonies can reach sizes of over eight million individuals, with underground nests that grow larger than 30 metres across. The lives of leafcutter ants revolve around a fungus which they cultivate in cavernous chambers and feed with fragments of leaf.[8]

Human societies are no less entwined with fungi. Diseases caused by fungi cause billions of dollars of losses – the rice blast fungus ruins a quantity of rice large enough to feed more than sixty million people every year. Fungal diseases of trees, from Dutch elm disease to chestnut blight, transform forests and landscapes. Romans prayed to the god of mildew, Robigus, to avert fungal diseases but weren’t able to stop the famines that contributed to the decline of the Roman Empire. The impact of fungal diseases is increasing across the world: unsustainable agricultural practices reduce the ability of plants to form relationships with the beneficial fungi on which they depend. The widespread use of antifungal chemicals has led to an unprecedented rise in new fungal superbugs that threaten both human and plant health. As humans disperse disease-causing fungi, we create new opportunities for their evolution. Over the last fifty years, the most deadly disease ever recorded – a fungus that infects amphibians – has been spread around the world by human trade. It has driven ninety species of amphibian to extinction and threatens to wipe out over a hundred more. The variety of banana that accounts for 99 per cent of global banana shipments, the Cavendish, is being decimated by a fungal disease and faces extinction in the coming decades.[9]

Like leafcutter ants, however, humans have worked out how to use fungi to solve a range of pressing problems. In fact, we have probably deployed fungal solutions for longer than we have been *Homo sapiens*. In 2017, researchers reconstructed the diets of Neanderthals, cousins of modern humans who went extinct approximately 50,000 years ago. They found that an individual with a dental abscess had been eating a type of fungus, a penicillin-producing mould, implying knowledge of its antibiotic properties. There are other less ancient examples, including 'the Iceman', an exquisitely well-preserved Neolithic corpse found in glacial ice, dating from around 5,000 years ago. On the day he died, the Iceman was carrying a pouch stuffed with wads of the tinder fungus (*Fomes fomentarius*) that he almost certainly used to make fire, and carefully prepared fragments of the birch polypore mushroom (*Fomitopsis betulina*) most probably used as a medicine.[10]

The indigenous peoples of Australia treated wounds with moulds harvested from the shaded side of eucalyptus trees. The Jewish Talmud features a mould cure known as 'chamka', consisting of mouldy corn soaked in date wine. Ancient Egyptian papyruses from 1500 BCE refer to the curative properties of mould, and in 1640 the King's herbalist in London, John Parkinson, described the use of moulds to treat wounds. But it was only in 1928 that Alexander Fleming discovered that a mould produced a bacteria-killing chemical called penicillin. Penicillin became the first modern antibiotic and has since saved countless lives. Fleming's discovery is widely credited as one of the defining moments of modern medicine, and arguably helped to shift the balance of power in the Second World War.[11]

Penicillin, a compound that could defend fungi from bacterial infection, turned out to defend humans as well. This is not unusual: although fungi have long been lumped together with plants, they are actually more closely related to animals – an example of the kind of category mistake researchers regularly make in their struggle to understand fungal lives. At a molecular level, fungi and humans are similar enough to benefit from many of the same biochemical innovations. When we use drugs produced by fungi we are often borrowing a fungal solution and rehousing it within our own bodies. Fungi are pharmaceutically prolific, and today we depend on them for many other chemicals besides penicillin: cyclosporine (an immunosuppressant drug that makes organ transplants possible), cholesterol-lowering statins, a host of powerful antiviral and anti-cancer compounds (including the multi-billion-dollar drug Taxol, originally extracted from the fungi that live within yew trees), not to mention alcohol (fermented by a yeast) and psilocybin (the active component in psychedelic mushrooms recently shown in clinical trials to be capable of lifting severe depression and anxiety). Sixty per cent of the enzymes used in industry are generated by fungi, and 15 per cent of all vaccines are produced by engineered strains of yeast. Citric acid, produced by fungi, is used in all fizzy drinks. The global market for edible fungi is booming, and projected to increase from $42 billion in 2018 to $69 billion by 2024. Sales of medicinal mushrooms are increasing yearly.[12]

Fungal solutions don't stop at human health. Radical fungal technologies can help us respond to some of the many problems that arise from ongoing environmental devastation. Antiviral compounds produced by fungal mycelium reduce colony collapse disorder in honeybees. Voracious fungal appetites can be deployed to break down pollutants such as crude oil from oil spills, in a process known as 'mycoremediation'. In 'mycofiltration', contaminated water is passed through mats of mycelium which filter out heavy metals and break down toxins. In 'mycofabrication', building materials and textiles are grown out of mycelium and replace plastics and leather in many applications. Fungal melanins, the pigments produced by radio-tolerant fungi, are a promising new source of radiation-resistant biomaterials.[13]

Human societies have always pivoted around prodigious fungal metabolisms. A full litany of the chemical accomplishments of fungi would take months to recite. Yet despite their promise, and central role in many ancient human fascinations, fungi have received a tiny fraction of the attention given to animals and plants. The best estimate suggests that there are between 2.2 and 3.8 million species of fungi in the world – six to ten times the estimated number of plant species – meaning that a mere 6 per cent of all fungal species have been described. We are only just beginning to understand the intricacies and sophistications of fungal lives.[14]

For as long as I can remember I've been fascinated by fungi and the transformations they provoke. A solid log becomes soil, a lump of dough rises into bread, a mushroom erupts overnight – but how? As a teenager I dealt with my bafflement by finding ways to involve myself with fungi. I picked mushrooms, and grew mushrooms in my bedroom. Later, I brewed alcohol in the hope that I might learn more about yeast and its influence on me. I marvelled at the transformation of honey into mead, and fruit juice into wine – and at how the product of these transformations could transform my own senses and those of my friends.

By the time my formal study of fungi began, when I became an undergraduate at Cambridge in the Department of Plant Sciences – there is no Department of Fungal Sciences – I had become fascinated by symbiosis – the close relationships that form between unrelated organisms. The history of life turned out to be full of intimate collaborations. Most plants, I learned, depend on fungi to provide them with nutrients from the soil, such as phosphorus or nitrogen, in exchange for energy-giving sugars and lipids produced in photosynthesis – the process by which plants eat light and carbon dioxide from the air. The relationship between plants and fungi gave rise to the biosphere as we know it and supports life on land to this day, but we seemed to understand so little. How did these relationships arise? How do plants and fungi communicate with one another? How could I learn more about the lives of these organisms?

I accepted the offer of a PhD to study mycorrhizal relationships in tropical forests in Panama. Soon afterwards, I moved to a field station on an island run by the Smithsonian Tropical Research Institute. The island and surrounding peninsulas were part of a nature reserve entirely covered by forest, apart from a clearing for dormitories, a canteen and lab buildings. There were greenhouses for growing plants, drying cupboards filled with bags of leaf litter, a room lined with microscopes, and a walk-in freezer packed with samples: bottles of tree sap, dead bats, tubes containing ticks pulled from the backs of spiny rats and boa constrictors. Posters on the noticeboard offered cash rewards to anyone who could source fresh ocelot droppings from the forest.

The jungle bristled with life. There were sloths, pumas, snakes, crocodiles; there were basilisk lizards that could run across the surface of water without sinking. In just a few hectares there lived as many woody plant species as in the whole of Europe. The diversity of the forest was reflected in the rich variety of field biologists who came there to study it. Some climbed trees and observed ants. Some set out at dawn every day to follow the monkeys. Some tracked the lightning that struck trees during tropical storms. Some spent their days suspended from a crane measuring ozone concentrations in the forest canopy. Some warmed up the soil using electrical elements to see how bacteria might respond to global heating. Some studied the way beetles navigate using the stars. Bumblebees, orchids, butterflies – there seemed to be no aspect of life in the forest that someone wasn't observing.

I was struck by the creativity and humour of this community of researchers. Lab biologists spend most of their time in charge of the pieces of life they study. Their own human lives are lived outside the flasks that contain their subject matter. Field biologists rarely have so much control. The world is the flask and they're inside it. The balance of power is different. Storms wash away the flags that mark their experiments. Trees fall on their plots. Sloths die where they planned to measure the nutrients in the soil. Bullet ants sting them as they crash past. The forest and its inhabitants dispel any illusions that scientists are in charge. Humility quickly sets in.

The relationships between plants and mycorrhizal fungi are key to understanding how ecosystems work. I wanted to learn more about the way nutrients passed through fungal networks, but I became dizzy when I thought about what was going on underground. Plants and mycorrhizal fungi are promiscuous: many fungi can live within the roots of a single plant, and many plants can connect with a single fungal network. In this way a variety of substances, from nutrients to signalling compounds, can pass between plants via fungal connections. In simple terms, plants are socially networked by fungi. This is what is meant by the 'Wood Wide Web'. The tropical forests I worked in contained hundreds of plant and fungal species. These networks are inconceivably complicated, their implications huge and still poorly understood. Imagine the puzzlement of an extraterrestrial anthropologist who discovered, after decades of studying modern humanity, that we had something called the Internet. It's a bit like that for contemporary ecologists.

In my efforts to investigate the networks of mycorrhizal fungi that strung their way through the soil, I collected thousands of soil samples and tree root trimmings and mashed them into pastes to extract their fats, or DNA. I grew hundreds of plants in pots with different communities of mycorrhizal fungus and measured how big their leaves grew. I sprinkled thick rings of black pepper around the greenhouses to deter cats from creeping in and bringing with them rogue fungal communities from outside. I dosed plants with chemical labels and traced these chemicals through roots and into the soil so that I might measure how much must have passed to their fungal associates – more mashing and more pastes. I spluttered around the forested peninsulas in a small motorboat that often broke down, climbed up waterfalls looking for rare plants, trudged for miles down muddy paths carrying a backpack full of waterlogged soil, and drove trucks into drifts of thick red jungle mud.

Of the many organisms that lived in the rainforest, I was most enthralled by a species of small flower that sprouted from the ground. These plants were the height of a coffee cup, their stalks spindly and pale white with a single bright blue flower balanced on top. They were a species of jungle gentian called *Voyria*, and had long ago lost the ability to photosynthesise. In doing so they had lost their chlorophyll, the pigment that makes photosynthesis possible and gives plants their green colour. I was perplexed by *Voyria*. Photosynthesis is one of the things that makes plants plants. How could these plants survive without it?

I suspected *Voyria's* relationships with their fungal partners were unusual, and I wondered whether these flowers might tell me something about what was going on below the surface of the soil. I spent many weeks searching for *Voyria* in the jungle. Some flowers grew in open stretches of the forest and were easy to spot. Others hid, tucked behind buttressed tree roots. Within plots a quarter of the size of a football pitch there could be hundreds of flowers, and I had to count them all. The forest was rarely open or flat, so this meant scrambling and stooping. In fact, it meant almost anything but walking. Each evening I returned to the field station filthy and exhausted. Over supper my Dutch ecologist friends cracked jokes about my cute blossoms with their frail stems. They studied the ways that tropical forests stored carbon. While I scuffed along squinting at the ground in search of tiny flowers, they measured the girth of trees. In a carbon budget of the forest, *Voyria* were inconsequential. My Dutch friends teased me about my small ecology and my dainty fascinations. I teased them about their brute ecology and their machismo. At dawn the next day, I would set off once again, peering at the floor in the hope that these curious plants could help me find my way underground, into this hidden, teeming world.

Whether in forests, labs or kitchens, fungi have changed my understanding of how life happens. These organisms make questions of our categories and thinking about them makes the world look different. It was my growing delight in their power to do so that led me to write this book. I have tried to find ways to enjoy the ambiguities that fungi present, but it's not always easy to be comfortable in the space created by open questions. Agoraphobia can set in. It's tempting to hide in small rooms built from quick answers. I have done my best to hold back.

A friend of mine, the philosopher and magician David Abram, used to be the house magician at Alice's Restaurant, in Massachusetts (made famous by the Arlo Guthrie song). Every night he passed around the tables; coins walked through his fingers, reappeared exactly where they shouldn't, disappeared again, divided in two, vanished into nothing. One evening, two customers returned to the restaurant shortly after leaving and pulled David aside, looking troubled. When they left the restaurant, they said, the sky had appeared shockingly blue and the clouds large and vivid. Had he put something in their drinks? As the weeks went by, it continued to happen – customers returned to say the traffic had seemed louder than it was before, the streetlights brighter, the patterns on the sidewalk more fascinating, the rain more refreshing. The magic tricks were changing the way people experienced the world.

David explained to me why he thought this happened. Our perceptions work in large part by expectation. It takes less cognitive effort to make sense of the world using preconceived images updated with a small amount of new sensory information than to constantly form entirely new perceptions from scratch. It is our preconceptions that create the blind spots in which magicians do their work. By attrition, coin tricks loosen the grip of our expectations about the way hands and coins work. Eventually, they loosen the grip of our expectations on our perceptions more generally. On leaving the restaurant, the sky looked different because the diners saw the sky as it was there and then, rather than as they expected it to be. Tricked out of our expectations, we fall back on our senses. What's astonishing is the gulf between what we expect to find, and what we find when we actually look.[15]

Fungi, too, trick us out of our preconceptions. Their lives and behaviours are startling. The more I've studied fungi, the more my expectations have loosened, and the more familiar concepts have started to appear unfamiliar. Two fast-growing fields of biological enquiry have helped me both navigate these states of surprise and provide frameworks that have guided my exploration of the fungal world.

The first is a growing awareness of the many sophisticated, problem-solving behaviours that have evolved in brainless organisms outside the animal kingdom. The best-known examples are slime moulds, such as *Physarum polycephalum* (though they are amoeba, not fungi, as true moulds are). As we'll see, slime moulds have no monopoly on brainless problem-solving, but they are easy to study and have become poster organisms that have opened up new avenues of research. *Physarum* form exploratory networks made of tentacle-like veins, and have no central nervous system – or anything that resembles one. Yet they can 'make decisions' by comparing a range of possible courses of action, and can find the shortest path between two points in a labyrinth. Japanese researchers released slime moulds into petri dishes modelled on the Greater Tokyo area. Oat flakes marked major urban hubs and bright lights represented obstacles such as mountains – slime moulds don't like light. After a day, the slime mould had found the most efficient route between the oats, emanating into a network almost identical to Tokyo's existing rail network. In similar experiments, slime moulds have re-created the motorway network of the United States and the network of Roman roads in central Europe. A slime mould enthusiast told me about a test he had performed. He frequently got lost in IKEA stores, and would spend many minutes trying to find the exit. He decided to challenge his slime moulds with the same problem, and built a maze based on the floor plan of his local IKEA. Sure enough, without any signs or staff to direct them, the slime moulds soon found the shortest path to the exit. 'You see,' he said with a laugh, 'they're cleverer than me.'[16]

Whether one calls slime moulds, fungi and plants 'intelligent' depends on one's point of view. Classical scientific definitions of intelligence use humans as a yardstick by which all other species are measured. According to these anthropocentric definitions, humans are always at the top of the intelligence rankings, followed by animals that look like us (chimpanzees, bonobos, etc.), followed again by other 'higher' animals, and onwards and downwards in a league table – a great chain of intelligence drawn up by the ancient Greeks, which persists one way or another to this day. Because these organisms don't look like us or outwardly behave like us – or have brains – they have traditionally been allocated a position somewhere at the bottom of the scale. Too often they are thought of as the inert backdrop to animal life. Yet many are capable of sophisticated behaviours that prompt us to think in new ways about what it means for organisms to 'solve problems', 'communicate', 'make decisions', 'learn' and 'remember'. As we do so, some of the vexed hierarchies that underpin modern thought start to soften. As they soften, our ruinous attitudes towards the more-than-human world may start to change.[17]

The second field of research that has guided me in this enquiry concerns the way we think about the microscopic organisms – or microbes – that cover every inch of the planet. In the last four decades, new technologies have granted unprecedented access to microbial lives. The outcome? For your community of microbes – your 'microbiome' – your body is a planet. Some prefer the temperate forest of your scalp, some the arid plains of your forearm, some the tropical forest of your crotch or armpit. Your gut (which if unfolded would occupy an area of 32 square metres), ears, toes, mouth, eyes, skin and every surface, passage and cavity you possess teem with bacteria and fungi. You carry around more microbes than your 'own' cells. There are more bacteria in your gut than stars in our galaxy.[18]

For humans, identifying where one individual stops and another starts is not generally something we think about. It is usually taken for granted – within modern industrial societies, at least – that we start where our bodies begin and stop where our bodies end. Developments in modern medicine, such as organ transplants, worry these distinctions; developments in the microbial sciences shake them at their foundations. We are ecosystems, composed of – and decomposed by – an ecology of microbes, the significance of which is only now coming to light. The 40 trillion-odd microbes that live in and on our bodies allow us to digest food and produce key minerals that nourish us. Like the fungi that live within plants, they protect us from disease. They guide the development of our bodies and immune systems and influence our behaviour. If not kept in check, they can cause illnesses, and even kill us. We are not a special case. Even bacteria have viruses within them (a nanobiome?). Even viruses can contain smaller viruses (a picobiome?). Symbiosis is a ubiquitous feature of life.[19]

I attended a conference in Panama on tropical microbes, and along with many other researchers spent three days becoming increasingly bewildered by the implications of our studies. Someone got up to talk about a group of plants that produced a certain group of chemicals in their leaves. Until then, the chemicals had been thought of as a defining characteristic of that group of plants. However, it transpired that the chemicals were actually made by fungi that lived in the leaves of the plant. Our idea of the plant had to be redrawn. Another researcher interjected, suggesting that it may not be the fungi living inside the leaf that produced these chemicals, but the bacteria living inside the fungus. Things continued along these lines. After two days, the notion of the individual had deepened and expanded beyond recognition. To talk about individuals made no sense any more. Biology – the study of living organisms – had transformed into ecology – the study of the relationships between living organisms. To compound matters, we understood very little. Graphs of microbial populations projected on a screen had large sections labelled 'unknown'. I was reminded of the way that modern physicists portray the universe, more than ninety-five percent of which is described as 'dark matter' and 'dark energy'. Dark matter and energy are dark because we don't know anything about them. This was biological dark matter, or dark life.[20]

Many scientific concepts – from 'time' to 'chemical bonds' to 'genes' to 'species' – lack stable definitions but remain helpful categories to think with. From one perspective, 'individual' is no different: just another category to guide human thought and behaviour. Nonetheless, so much of daily life and experience – not to mention our philosophical, political and economic systems – depends on individuals that it can be hard to stand by and watch the concept dissolve. Where does this leave 'us'? What about 'them'? 'Me'? 'Mine'? 'Everyone'? 'Anyone'? My response to the discussions at the conference was not just intellectual. Like a diner at Alice's Restaurant, I felt different: the familiar had become unfamiliar. The 'loss of a sense of self-identity, delusions of self-identity and experiences of "alien control"', observed an elder statesman in the field of microbiome research, are all potential symptoms of mental illness. It made my head spin to think of how many ideas had to be revisited, not least our culturally treasured notions of identity, autonomy and independence. It is in part this disconcerting feeling that makes the advances in the microbial sciences so exciting. Our microbial relationships are about as intimate as any can be. Learning more about these associations changes our experience of our own bodies and the places we inhabit. 'We' are ecosystems that span boundaries and transgress categories. Our selves emerge from a complex tangle of relationships only now becoming known.[21]

The study of relationships can be confusing. Almost all are ambiguous. Have leafcutter ants domesticated the fungus they depend on, or has the fungus domesticated the ants? Do plants farm the mycorrhizal fungi they live with, or do the fungi farm the plants? Which way does the arrow point? This uncertainty is healthy.

I had a professor called Oliver Rackham, an ecologist and historian, who studied the ways in which ecosystems have shaped – and been shaped by – human cultures for thousands of years. He took us to nearby forests, and told us about the history of these places and their human inhabitants by reading the twists and splits in the branches of old oak trees, by observing where nettles thrived, by noting which plants did or didn't grow in a hedgerow. Under Rackham's influence, the clean line I had imagined dividing 'nature' and 'culture' started to blur.

Later, doing fieldwork in Panama, I came across many complicated relationships between field biologists and the organisms they studied. I joked with the bat scientists that in staying up all night and sleeping all day they were learning bat habits. They asked how the fungi were imprinting themselves on me. I'm still not sure. But I continue to wonder how, in our total dependence on fungi – as regenerators, recyclers, and networkers that stitch worlds together – we might dance to their tune more often than we realise.

If we do, it's easy to forget. Too often, I become detached and see the soil as an abstract place, a vague arena for schematic interactions. My colleagues and I say things like, '(So-and-so) reported an approximate 25 per cent increase in soil carbon from one dry season to the next wet season.' How can we not? We have no way to experience the wilds of the soil and the countless lives that froth away within it.

With the available tools, I tried. Thousands of my samples passed through expensive machines that whisked, irradiated and blasted the contents of the tubes into strings of numbers. I spent whole months staring into a microscope, immersed in rootscapes filled with winding hyphae frozen in ambiguous acts of intercourse with plant cells. Still, the fungi I could see were dead, embalmed and rendered in false colours. I felt like a clumsy sleuth. While I crouched for weeks scraping mud into small tubes, toucans croaked, howler monkeys roared, lianas tangled and anteaters licked. Microbial lives, especially those buried in soil, were not accessible like the bristling, charismatic, above-ground world of the large. Really, to make my findings vivid, to allow them to build and contribute to a general understanding, imagination was required. There was no way around it.

In scientific circles imagination usually goes by the name of speculation and is treated with some suspicion – in publications it is usually served up with a mandatory health warning. Part of writing up research is scrubbing it clean of the flights of fancy, idle play and thousand trials and errors that give rise to even the smallest of findings. Not everyone who reads a study wants to push their way through the fuss. Besides, scientists have to appear credible. Sneak backstage and one might not find people at their most presentable. Even backstage, in the most nocturnal musings I shared with colleagues, it was unusual to get into the details of how we had imagined – accidentally or deliberately – the organisms we studied, whether fish, bromeliad, liana, fungus or bacterium. There was something embarrassing about admitting that the tangle of our unfounded conjectures, fantasies and metaphors might have helped shape our research. Regardless, imagination forms part of the everyday business of enquiring. Science isn't an exercise in cold-blooded rationality. Scientists are – and have always been – emotional, creative, intuitive, whole human beings, asking questions about a world that was never made to be catalogued and systematised. Whenever I asked what these fungi were doing and designed studies to try and understand their behaviours, I necessarily imagined them.

An experiment forced me to peer into the deeper recesses of my scientific imagination. I signed up to take part in a clinical study into the effects of LSD on the problem-solving abilities of scientists, engineers and mathematicians. The study was part of the wide revival of scientific and medical interest in the untapped potential of psychedelic drugs. The researchers wanted to know if LSD could grant scientists access to their professional unconscious and help them approach familiar problems from new angles. Our imaginations, usually brushed aside, were to be the stars of the show, the phenomena being observed and potentially even measured. An eclectic group of young researchers had been enlisted through posters in science departments around the country ('Do you have a meaningful problem that needs solving?'). It was a brave study. Creative breakthroughs are notoriously hard to facilitate anywhere, let alone in the clinical drug trial unit of a hospital.

The researchers running the experiment had arranged psychedelic hangings on the walls, set up a sound system for music to be piped in and lit the room with coloured 'mood lights'. Their attempts to de-clinicalise the setting made it seem more artificial: an admission of the impact that they – the scientists – might have on their subject matter. It was an arrangement that made visible many of the healthy insecurities faced by researchers on a day-to-day basis. If only the subjects of all biological experiments were provided with their equivalent of mood lighting and relaxing music, how differently they might behave.

The nurses made sure I drank the LSD at exactly 9 a.m. They watched me closely until I had swallowed all the liquid, which had been mixed in a small wine glass's worth of water. I lay down on the bed in my hospital room and the nurses sucked a sample of blood through the cannula in my forearm. Three hours later, when I had reached 'cruising altitude', I was gently encouraged by my assistant to start thinking about my 'work-related problem'. Amid the battery of psychometric tests and personality assessments we had completed before the trip, we had been asked to describe our problems in as much detail as possible – those knots in our enquiries we might be fumbling with. Soaking the knots in LSD might help them loosen. All my research questions were fungal ones, and I was comforted by the knowledge that LSD was originally derived from a fungus that lives within crop plants; a fungal solution to my fungal problems. What would happen?

I wanted to use the LSD trial to think more broadly about the lives of the blue flowers, *Voyria*, and their fungal relationships. How did they live without photosynthesis? Almost all plants sustain themselves by drawing minerals from mycorrhizal fungal networks in the soil; so did *Voyria*, judging by the tousled mass of fungi that crowded into their roots. But without photosynthesis, *Voyria* had no way to make the energy-rich sugars and lipids they needed to grow. Where did *Voyria* get their energy from? Could these flowers draw substances from other green plants via the fungal networks? If so, did *Voyria* have anything to give back to their fungal partners in exchange, or were they just parasites – hackers of the Wood Wide Web?

I lay on the hospital bed with my eyes closed and wondered what it was like to be a fungus. I found myself underground, surrounded by growing tips surging across one another. Schools of globular animals grazing – plant roots and their hustle – the Wild West of the soil – all those bandits, brigands, loners, crap shooters. The soil was a horizonless external gut – digestion and salvage everywhere – flocks of bacteria surfing on waves of electrical charge – chemical weather systems – subterranean highways – slimy infective embrace – seething intimate contact on all sides. As I followed a fungal hypha into a cavernous root, I was struck by the sanctuary it offered. Very few other types of fungi were present; certainly no worms or insects. There was less bustle and hassle. It was a haven I could imagine paying for. Perhaps that was what the blue flowers offered the fungi in return for their nutritional support? Shelter from the storm.

I make no claims about the factual validity of these visions. They are at best plausible, and at worst delirious nonsense. Not even wrong. Nonetheless, I learned a valuable lesson. The way I had grown accustomed to thinking about fungi involved abstract 'interactions' between organisms that actually looked like the diagrams schoolteachers drew on the board: semi-automatic entities that behaved according to an early-Nineties Game Boy logic. However, the LSD had forced me to admit that I had an imagination, and I now saw fungi differently. I wanted to understand fungi, not by reducing them to ticking, spinning, bleeping mechanisms, as we so often do. Rather, I wanted to let these organisms lure me out of my well-worn patterns of thought, to imagine the possibilities they face, to let them press against the limits of my understanding, to give myself permission to be amazed – and confused – by their entangled lives.

Fungi inhabit enmeshed worlds; countless threads lead through these labyrinths. I have followed as many as I can, but there are crevices I haven't been able to squeeze through no matter how hard I've tried. Despite their nearness, fungi are so mystifying, their possibilities so *other*. Should this scare us off? Is it possible for humans, with our animal brains and bodies and language, to learn to understand such different organisms? How might we find ourselves changed in the process? In optimistic moods, I've imagined this book to be a portrait of this neglected branch of the tree of life, but it's more tangled than that. It is an account both of my journey towards understanding fungal lives, and of the imprint fungal lives have left on me and the many others I've met along the road, human or otherwise. 'What shall I do with the night and the day, with this life and this death?' writes the poet Robert Bringhurst. 'Every step, every breath rolls like an egg towards the edge of this question.' Fungi roll us towards the edge of many questions. This book comes from my experience of peering over some of these edges. My exploration of the fungal world has made me re-examine much of what I knew. Evolution, ecosystems, individuality, intelligence, life – none are quite what I thought they were. My hope is that this book loosens some of your certainties, as fungi have loosened mine.

Mushroom spore print

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