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From Its Myriad Tips
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ENTANGLED LIFE: HOW FUNGI MAKE OUR WORLDS, CHANGE OUR MINDS AND SHAPE OUR FUTURES
by Merlin Sheldrake.
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TRY to imagine what it is like to be a fungus. Not a mushroom, pushing up through damp soil overnight or delicately forcing itself out through the bark of a rotting log: that would be like imagining the grape rather than the vine. Instead try to think your way into the main part of a fungus, the mycelium, a proliferating network of tiny white threads known as hyphae. Decentralised, inquisitive, exploratory and voracious, a mycelial network ranges through soil in search of food. It tangles itself in an intimate scrawl with the roots of plants, exchanging nutrients and sugars with them; it meets with the hyphae of other networks and has mycelial sex; messages from its myriad tips are reported rapidly across the whole network by mysterious means, perhaps chemical, perhaps electrical. For food, it prefers wood, but with practice it can learn to eat novel substances, including toxic chemicals, plastics and oil. Is it somehow sentient? As its thousands of hyphae simultaneously but independently rove through the soil, is the mycelium behaving as an individual or a swarm? What is it like to be this way?

An ant infected by the fungus Ophiocordyceps. Photograph © Linden Glendhill, 2011

Merlin Sheldrake has tried imagining it:

> 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.

Sheldrake is reporting the results of an experiment. He had been dosed with LSD (a compound originally synthesised from ergot, a fungus that affects rye), as part of a study investigating whether scientists might gain unexpected insights by thinking about their work while tripping. Sheldrake's work was on mycorrhizal fungi, which form mutually beneficial relationships with plants via their roots. He wanted to understand how and why they had learned to do this, and how in turn some plants, known as mycoheterotrophs, have developed such powerful relationships with fungi that they no longer need to bother with photosynthesis. Almost all plants require mycorrhizal partners to be healthy – more than 90 per cent of plants rely on them, Sheldrake says, making fungal partners a 'more fundamental part of planthood than fruit, flowers, leaves, wood or even roots' – but mycoheterotrophs can sustain themselves exclusively on the energy provided by their fungal consociates. These plants have substituted out the sun as their source of power, and as a result have lost their chlorophyll and are no longer green. Some have evolved new colours, like the flaming crimson *Sarcodes sanguinea*; some have lost colour altogether, like the ghostpipe, *Monotropa uniflora*, with its pallid white stalks and flowers.

Sheldrake took a particular interest in *Voyria tenella*, a delicate, blue-flowered forest gentian that grows in South and Central American rainforests. *Voyria*'s reliance on its mycorrhizal partners is so complete that its roots struggle to absorb water and minerals on their own. The fungus may also be extracting sugars and lipids from other nearby plants, further servicing the flower's needs. *Voyria* clearly has a good thing going, but what's in it for the fungus? Does the flower give its fungal partner something in exchange, or is it a true parasite, using its mycorrhizal companion to hack into the energy resources of the forest?

Lab grade acid dropped, Sheldrake laughed and dreamed his way to some hypotheses about the fungus that were 'at best plausible, and at worst delirious nonsense'. There is no solution yet to the problem of *Voyria*. Much of fungal behaviour is mysterious; this is one of the central themes of *Entangled Life*. Though they seem familiar from woodland walk and supermarket punnet, fungi are strange and challenging organisms. A biological kingdom unto themselves, they do not behave like plants or like animals. They habitually form intimate partnerships with other species, changeable and volatile relationships which slide ambiguously beyond the bounds of the more familiar symbiosis or parasitism. Lichens, for instance, whose existence is often glossed as a symbiosis between plant and fungus, are such compressed bundles of life that it might be better to think of them as miniature ecosystems in themselves, comprising numerous different tiny plants and fungi in dense and inseparable embrace.

Lichens are some of the hardiest beings on earth, thriving in the most extreme environments. There are lichens that are impervious to radiation, to burning heat, to freezing cold. Some can happily survive periods in space, unprotected from solar radiation – evidence, for some, of the plausibility of panspermia, the idea that life arrived from outer space. Perhaps it was tiny lichenous ecosystems, dormant for thousands of years on chunks of spinning rock smashed out of distant planetary collisions, that crossed the abyss between worlds to seed the cosmos with life. Fungi certainly seem to have been one of the first complex living things on earth: fossils of what look like mycelium have been found in rocks 2.4 billion years old. It was only through fungal assistance that the first rootless plants were able to colonise the land at all; on the barren rocks of the early earth, fungi were already thriving when the first algae began to leave the sea. And for fifty million years, fungi did all the work of roots for the first land-dwelling plants. It's possible that roots evolved in order to house them.

Lichens are an extreme case in their propensity to form partnerships, but with fungi, even the seemingly singular are many: fungal genomes are so promiscuous and multiple that some scholars have proposed abandoning the attempt to categorise them using the Linnaean system. They are everywhere, all the time: coursing through soil and seabed, '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 the canvases of old master paintings hanging in museums'. If the mycelial threads in just a teaspoon of soil were unravelled and laid out, they might stretch anywhere from 'a hundred metres to ten kilometres'. Mycelium is a continuous mesh that envelops the earth – strangely, differently, alive and alert.

Modern research into fungi's differentness has only increased our uncertainty as to what kind of organism they really are. In the conventional account, animals move around, do things, and are sentient; plants are sessile, typically move only very slowly by growing, and aren't really sentient. That schematic distinction between the two great kingdoms of complex living things has turned out to be naive and limited, especially when it comes to plants, to which fungi were considered akin – the guidebooks used to call them 'flowerless plants'. But the lives of fungi don't seem to be very much like the lives of plants at all, and in some ways they behave more like animals.

Take the proficiency of fungi at problem-solving. Fungi are used to searching out food by exploring complex three-dimensional environments such as soil, so maybe it's no surprise that fungal mycelium solves maze puzzles so accurately. It is also very good at finding the most economical route between points of interest. The mycologist Lynne Boddy once made a scale model of Britain out of soil, placing blocks of fungus-colonised wood at the points of the major cities; the blocks were sized proportionately to the places they represented. Mycelial networks quickly grew between the blocks: the web they created reproduced the pattern of the UK's motorways ('You could see the M5, M4, M1, M6'). Other researchers have set slime mould loose on tiny scale-models of Tokyo with food placed at the major hubs (in a single day they reproduced the form of the subway system) and on maps of Ikea (they found the exit, more efficiently than the scientists who set the task). Slime moulds are so good at this kind of puzzle that researchers are now using them to plan urban transport networks and fire-escape routes for large buildings.

Mycelium not only grows into economical networks, it also reshapes itself in response to its environment. From a block of colonised wood, teeming hyphae initially grow out in all directions in search of more food. But when one part of the network finds something new to consume – another block of wood, for instance – the rest of the mycelium stops searching, withdraws from fruitless areas and begins thickening the links to the new food source. What's more, if the hyphae that connect the original block of wood to the newly discovered one are stripped away, and the two blocks are placed in a new container to prevent the re-establishment of old pathways, the regrowing mycelium will nevertheless start out of the original block in the direction of the other one: it appears to 'possess a directional memory, although the basis of this memory is unknown'.

'Solving mazes and complex routing problems are non-trivial exercises,' Sheldrake writes. 'This is why mazes have long been used to assess the problem-solving abilities of many organisms, from octopuses to bees to humans.' Fungi ace these puzzles because 'solving spatial and geometrical problems is what they have evolved to do.' They are diffuse, plastic beings: they reform themselves around the problem at hand. 'Mycelium', says Sheldrake, is a body without limits: 'a body without a plan'.

With a decentralised body that grows independently at every extremity, how does a fungus know when to change itself? When a hyphal tip discovers a tasty block of wood, how is this information conveyed to the rest of the network-body? Through chemical transport, perhaps? Fungi are known to produce and respond to chemicals that can act as cues, and mycelial networks transport water and nutrients rapidly through their hyphae in 'micro-tubules', which function hydraulically and are highly pressure-sensitive. They can also direct the flow towards particular areas: when it is time to produce a mushroom, for instance, the mycelium propels water into the growing fruit, sometimes under great pressure. A fruiting stinkhorn mushroom can crack through asphalt, exerting a force sufficient to lift about 130 kg.

However, as methods of communication go, chemical plumes and microflows of pressurised liquid aren't very fast – and the mycelium of some fungi can extend for kilometres. Would electricity fit the bill? In the 1990s, the Swedish mycologist Stefan Olsson began to investigate. Adapting techniques used to research the brains of insects, he inserted glass microelectrodes into the body of the honey fungus, a species that creates huge mycelial networks. Sure enough, the mycelium was producing electrical impulses 'at a rate very close to that of animals' sensory neurons', which travelled through the network along the hyphae. When a block of wood – a food source – was placed in contact with the wired-up mycelium, the rate of firing doubled; it returned to normal when the wood was removed. Controls with a plastic block of similar size showed that the fungus was identifying the wood, rather than merely responding to weight or contact. Olsson repeated the experiment with other species of fungi, obtaining the same results: he concluded that fungi use electrical signals for internal communication, reporting on what the hyphae find or what is happening around them. They are, Sheldrake writes, 'fantastically complex networks of electrically excitable cells'.

Some researchers compare mycelial networks to brains, others to computers. Both images are seductive: the first suggests fantastical beings, extending themselves in contemplative ingestion through forest and field; the second invites speculation that mycelium's ability to sample and report on its surroundings might somehow be harnessed as a kind of 'biocomputing', capable of providing finely textured real-time reports on the health of the environment. Sheldrake cautions that neither metaphor truly gets close to the reality of mycelial lives, but he seems quite taken with them nonetheless. Likewise, Olsson dismisses the brain analogy, yet when observing that hyphal branching creates junctions that could act as 'decision gates' to integrate the streams of impulses from the foraging tips, he can't resist wondering if mycelium might indeed act like 'a "brain" that could learn and remember'.

Whether or not mycelium in fact behaves like a neural network, fungi certainly seem to have a highly evolved interest in the brains and nervous systems of others. The psychoactive effects that psilocybin-producing mushrooms have on humans are well known (though seriously under-researched), but the most virtuosic feats of mind alteration – if that is the right way to describe it – are performed by the numerous species of fungus that can control the minds and bodies of insects. These are sometimes called 'zombie fungi', and they act with what Sheldrake describes as 'exquisite precision'. The fungus *Ophiocordyceps* infects carpenter ants. Inside the body of an infected ant, it begins to develop a mycelial network. Hyphae travel through the ant's body cavities, into its limbs and organs: an infected insect becomes about 40 per cent fungus. Once this fungal growth is complete, the normally ground-dwelling ant leaves its nest and climbs the nearest plant. At a height of around 25 centimetres – 'a zone with just the right temperature and humidity to allow the fungus to fruit' – it orients itself towards the sun; at high noon, it clamps its jaws round a leaf vein, in a 'death grip'. Mycelium grows out of the ant's feet, plastering it to the leaf. Sutured into place, jaws rigid, the ant's body is then digested by the fungus: a small mushroom grows out of the ant's head, releasing spores which drift down onto the ants passing below, beginning the cycle again.

Massospora, a species completely unrelated to *Ophiocordyceps*, infects cicadas: it rots away the abdomen of an infected insect, leaving it tipped with a yellowish plug of spores that looks like a mass of pollen. Infected cicadas are not incapacitated or ill: in fact they become 'hyperactive and hypersexual despite the fact that their genitals have long since crumbled away'. Rushing between mates, they become 'flying salt-shakers of death', dusting other cicadas with *Massospora*'s spores.

It's unclear how such exact behavioural changes are effected. *Ophiocordyceps* fills an ant's body with hyphae and takes control of its actions, but it doesn't invade the ant's brain, which is left intact; *Massospora* confines itself pretty much to the cicada's abdomen, leaving the rest of the body alone, in order that the insect can continue to move around and attempt to mate while the fungus completes its life-cycle. It is possible that the control is achieved by means of minutely precise pharmacological interventions in the brains of the hosts: *Massospora* manufactures both psilocybin and cathinone, a stimulant related to the recreational drug mephedrone, which is otherwise found only in plants such as khat (*Catha edulis*, whose leaves are chewed widely in East Africa and beyond). So the fungus is perhaps administering both amphetamines and psychedelics to its cicada. But nobody really understands quite how this would work. The mechanism by which *Ophiocordyceps* produces exact and perfectly timed bodily actions in an infected ant is also a profound mystery, except that it most probably involves 'fine-tuning' the ant's 'chemical secretions in real time'.

Precise and complex effects of this sort are far beyond the reach of human medical pharmacology; Sheldrake compares the way these fungi command their hosts to phenomena such as spirit possession or the speech of mediums. Like an incorporeal spirit, the fungus does not have a body, instead entering and possessing something else's. The ascent up the plant and the death grip are not the behaviour of the carpenter ant but of the fungus, which is using the insect as a kind of exo-suit: 'For part of its life, *Ophiocordyceps* must wear an ant's body.' How rapidly, how finely must the network be communicating and acting to puppeteer the central nervous system of a living creature, to measure distance and conditions, to determine direction and time of day? The question of fungal sentience hovers in the background, like the ambiguous ghosts of spirit photography.

These ideas spill over into a discussion of the effects of psilocybin on humans. Sheldrake's parents were friends with Terence McKenna, the ethnobotanist, renegade philosopher and advocate of psychedelics, and it was on a visit to McKenna's Hawaiian home – whose grounds were a sort of Wonka Factory of psychoactive plants – that the young Merlin first learned that 'humans can alter their minds by eating other organisms.' McKenna speculated that psilocybin mushrooms lay at the root of human cultural development: it was consuming them which spurred the creation of art, culture, religion and even language. But he also believed that by means of a big enough dose of psilocybin, mushroom consciousness could manifest inside a human partner, and even communicate to the outside world: 'With psilocybin as a chemical messenger,' fungi could 'borrow a human body, and use its brain and senses to speak and think through.'

'Do psilocybin fungi wear our minds, as *Ophiocordyceps* and *Massospora* wear insect bodies?' Sheldrake asks. It's a marvellous, disorientating notion. But his answer is a qualified 'no': science has not found any evidence of a long-term evolutionary advantage for fungi in using psilocybin to form a symbiotic relationship with humans or their minds. Our eating them doesn't appear to help them in evolutionary terms; the timescales of human intervention are too short, and psilocybin-producing fungi have been around too long to care much about people. More likely, the compound developed to interfere with other beings, probably fungivorous insects.

But then again, Sheldrake writes, 'perhaps we shouldn't be too hasty' in giving up McKenna's notion. Sheldrake may, one suspects, have taken too many shrooms with too much fascination and joy to surrender the prospect that psilocybin might give us genuine insight into, or even a proxy experience of, fungal lives. Tripping on mushrooms is just too mushroom-y, too psychomycelial, to be set aside when trying to think about what fungi are up to. In the human brain, psilocybin suppresses what is called the 'default mode network', the interconnected brain areas responsible for self-reflection and self-consciousness, thinking about past and future, and for regulating other cerebral processes. The DMN, Sheldrake says, keeps a kind of order: 'a schoolteacher in a chaotic classroom'. In neural terms, psilocybin and LSD let the brain 'off the leash. Cerebral connectivity explodes, and a tumult of new neuronal pathways arise. Networks of activity previously distant from one another link up.' The experience of this for the user involves all the stereotypical (but reliably real) sensations: mystical gnosis, the revelation of the interconnectedness of all things, and so on.

Put like that, the patterns of thought experienced by someone taking psilocybin seem strikingly analogous to its neurological effects. And both seem profoundly similar to what we know of mycelium and its habits. The explosive growth of interconnections, the development of flexible new relationships, the filling of spaces with a tangle of new pathways, novel and powerful exchanges and flows of information coursing through an electrically excitable network: what else but this would a fungus do if it really did seize hold of your mind? And if a fungus were sentient or somehow like a brain, isn't this perhaps just how it would think – in an entanglement of intimate, sudden, pulsing, fresh connections between the things around it?