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Fungal Tech

Software Development Practices for a More-than-human World

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Abstract

This thesis explores ecologically-centred practices of software development, using fungi as a metaphor for fostering ecological, collaborative and resilient approaches to technology while giving agency to more-than-human forms of intelligence.

In light of the ongoing environmentally disastrous and in many respects alienating effects perpetuated by a technological industry that abstracts humanity from the living world, it critiques anthropocentric practices in software and emphasises the need for ecological criticality in digital tools.

Employing an embodied research process that integrates theoretical analysis, fieldwork and practice, it seeks to reimagine software development as a collective and ecological endeavour.

By bridging fungi-inspired ecological thought with ongoing efforts in academia and digital activism, it aims to contribute frameworks for building technologies rooted in interdependence, collective autonomy and systems thinking.

Introduction

Setting the Stage

We are living amidst several converging crises – ecological, energetic, political and economic. Rather than addressing the root causes of these challenges, the technology industry exacerbates them by (1) neglecting humanity's interdependence with living ecosystems, (2) consuming and extracting massive amounts of energy resources, (3) contributing to a concentration of power and wealth in the hands of an increasingly smaller number people, and (4) promoting a techno-centric faith in technology as the solution for endless economic growth on a finite planet.

In response, there is a pressing need for a new paradigm in technology – one that reimagines its design, production and purpose. This paradigm should prioritise (1) synergy and integration with the ecosystem, (2) decentralised and efficient energy practices, (3) a decentralised and democratised ownership, creation and transformation of technology, and (4) an acknowledgment of technology's limitations, fostering systems that support diverse life forms and non-growth centric economies.

Reshaping our technological paradigms is essential for fostering a future of living in reciprocity with the living world. This requires not just new tools but a fundamental rethinking of our relationship with technology, one that is willing to learn from more-than-human forms of intelligence – those expressions of agency and insight that exist in the non-human realm, such as fungi, plants, animals and ecosystems. This perspective challenges human-centred thinking, recognising more-than-human intelligences as active participants in shaping our shared world. In this thesis, I will draw parallels between the worlds of fungi and software development, seeking in fungi lessons in systems thinking, multi-species collaboration and collective resilience which can guide open-source makers, designers and developers towards more ecologically-centred tools.

Tool-making has long provided humans with a means of safety and survival, enabling activities like hunting, cooking, building settlements and communication, abilities regarded as foundational to human life. The Homeric hymn to Hephaestus (Hesiod 446), which links the advent of tool-making to the dawn of civilisation, reflects a pervasive belief in human exceptionalism. Despite being disproven by observations of various forms of tool creation and use in birds, primates and other mammals, this belief positions tool-making as a uniquely human ability (Seed and Byrne R1032) that elevates humanity above the rest of the living world, thereby devaluing the intelligences and agency of more-than-human beings.

For the purpose of this thesis, I view the creation of technology, including software development, as an extension of this historical practice of tool-making. Borrowing from Ursula K. Le Guin's definition of technology as "the active human interface with the material world" ("A Rant About 'Technology'"), I adopt a broad lens to consider technology as a key field where anthropocentrism manifests itself.

I will adopt Ben Mylius' definition of "normative anthropocentrism,"[1] referring to paradigms that privilege humanity, either passively, by constraining inquiry in ways that prioritise humans, or actively, by asserting the superiority of humans, their abilities, values or place in the universe, and making prescriptions based on these assumptions

[1] Mylius emphasises the importance of distinguishing between various forms of anthropocentrism – perceptual, descriptive and normative – to address significant misunderstandings surrounding the concept. They argue that anthropocentrism should not be limited to "a matter of normative claims about human superiority," which confines its relevance to the sub-field of environmental ethics, but instead recognised as a broader concern in philosophical inquiries (159-162). While this nuanced approach opens up a valuable discussion, engaging fully with these distinctions lies beyond the scope of this thesis. Here, I adopt Mylius' definition of normative anthropocentrism, focusing on paradigms that reinforce human superiority, and will refer to this simply as "anthropocentrism" throughout the thesis.

(159). This form of anthropocentrism underpins much of human exceptionalism, positioning human interests and abilities, such as the creation of tools and technology, as inherently superior to those of the more-than-human world.

The human tendency to define ourselves by our ability to create technology and justify this through notions of "superior intelligence" reinforces a hierarchical worldview which abstracts humanity from the broader ecological systems it is an inseparable part of. In this thesis, I challenge these assumptions, advocating for approaches to technology-making that recognise and collaborate with the broader web of life, aligning with ecological principles.

Ecology, described by the German naturalist Ernst Haeckel, who coined the term in the mid nineteenth century, as "the whole science of the relations of the organism to the environment including, in the broad sense, all the conditions of existence" (qtd. in Stauffer 140), offers a framework for understanding the relationships between humanity and the broader living world.

Part I.

In "**More-than-human Intelligences** And Why We Should Listen To Them,*"* I will argue that the ongoing climate crisis is deeply intertwined with anthropocentrism. Drawing on David Hinton's *Wild Mind, Wild Earth* (64-68), I will explore how the conceptual divide between the human mind and the material world is rooted in early technological changes in civilisation. This divide constrains our ways of thinking and building technology, which we have come to understand through a narrow, anthropocentric lens.

Based on critiques of the technology industry laid out by James Bridle (*New Dark Age* 68; *Ways of Being* 6, 10) and Kate Crawford (4-6, 15), I will show how this anthropocentric perspective continues to shape modern technology, which reflects and perpetuates values of human dominance and environmental exploitation. Building on Bridle's call in *Ways of Being* (14) to expand our understanding of intelligence, I will argue for engaging with fungal intelligence as a means to infuse technological practices with ecological thought.

I will highlight the relevance of fungi to community ecology theory, as argued by Thomas D. Bruns in *Fungal Ecology* (393, 396), as well as the humanities, where fungi have been talked about widely by authors whose writings inform this thesis, such as Anna Tsing (*The Mushroom at the End of the World*), Yasmine Ostendorf-Rodríguez (*Let's Become Fungal*) and Merlin Sheldrake (*Entangled Life*). I will then elaborate on how fungi, as the mediators in complex multi-species networks, embody a valuable model for systemic literacy. Drawing from Bridle's concept of systemic literacy in *New Dark Age*

(8-9) as a necessary precondition for developing criticality towards and fostering agency over technological systems, I will make the case for a posthumanist understanding of technology and ecology as interrelated and complex systems.

Coming back to Le Guin's definition of technology ("A Rant About 'Technology'") as the human interface with the material world, I will explore how mycorrhizal networks, which I describe as mycelial interfaces, serve as a model for rethinking technological interfaces in a regenerative way. By examining the role of mycorrhizal networks in supporting the health of ecosystems and their parallels with permacomputing – a community researching regenerative and resilient digital systems – I will argue for a shift in computational culture toward practices inspired by fungal principles. This section will set the stage for connecting these ecological insights to practical applications in software development further on (Part II.)

Part II

"**Making Better, Together:** Collectivising Access to Tools, Letting Go of Tech Solutionism and Embracing Collaboration in Place of Competition*"* will begin by exploring the similarities between mycorrhizal networks and open-source development communities to examine how decentralised systems can foster resilience through collaboration. Drawing parallels from the adaptability and inclusivity of mycelial networks, I will argue that open-source software could benefit from extending its collaborative ethos beyond programmers to include broader communities and ecological stakeholders. Grounding my arguments in an ongoing activist practice, I will use the collective Radical Data as a case study to investigate how open-source projects can extend their agency beyond technical users and embrace broader forms of situated and experiential knowledge.

While acknowledging the positive effects of situated technological projects, I will argue for the need for a deep, systemic change in the way we understand technological progress. Following Kate Soper's argument for adopting a post-growth paradigm as an ecological necessity in light of the ongoing climate crisis (8), I will lay out the groundwork necessary for such a radical shift in technological thinking. I will argue for abandoning the solutionist mindset that dominates the technology industry's current approaches to the climate crisis, which oversimplifies complex ecological issues while diverting attention from more meaningful systemic changes. Through a critique of Elon Musk's Mars colonisation project and Shell's Carbon Capture and Storage technologies, I will highlight how putting excessive faith in technological quick-fixes obstructs genuine ecological progress.

Departing from the argument that humanity's survival and well-being depend on the health of the commons – both material and intangible systems that sustain life – this section turns to the worlds of academia and activism for alternative software practices that counter tech-solutionism, which neglects these interconnected systems. Returning to the realm of fungi, I will highlight the viability of a survival strategy rooted in prioritising the health of broader living ecosystems. By aligning collaborative open-source practices with contextual awareness (3a), a respect of ecological limits and scale (3b) and collective autonomy (3c), I will explore how software development can play a crucial role in supporting the survival of the commons.

Drawing inspiration from fungi's deep awareness of their surroundings, I will (3a) reframe the technical process of dependency mapping as an ecological and social inquiry, moving beyond functional optimisation to consider the broader environmental and social entanglements of software and the infrastructure it relies on. I will argue that employing such a process can empower developers to align their practices with ecological principles and social accountability, contributing to a systemic shift toward technology rooted in contextual awareness and ecological literacy.

I will then explore (3b) how aligning computational practices within ecological limits and re-thinking the scale of technological projects can inform more sustainable and community-centered approaches to software development. Inspired by the adaptive resilience of fungi, particularly the matsutake mushroom, I will discuss how software design can thrive within ecological precarity by embracing simplicity, reducing energy consumption, and prioritising place-based initiatives. This discussion will incorporate insights from the Computing Within Limits research community, whose work emphasises the material impacts of computation and advocates for practices that respect planetary boundaries (Nardi et al. 86-87). Concepts such as cosmolocalism (Manzini 76; Kossof 52; Girard et al. 8-9), frugal innovation (Tomlinson 26) and decentralisation, exemplified by projects such as FarmHack and Open Source Ecology, will be highlighted as community-driven and localised alternatives to top-down, proprietary software, reducing reliance on environmentally damaging global systems.

Finally, I will lay out strategies (3c) for fostering collective autonomy – the capacity for communities to have agency over their technical needs – which I see as the most hopeful path towards transforming the way we design and sustain technology. Drawing from previous analyses of decentralised, community-driven and open-source approaches, I will argue for more significant, structural support for such projects in order to empower diverse communities to create tools that reflect their values and address local needs while contributing to the global commons.

I will discuss the role of modularisation, as demonstrated by Radical Data's work on *Queering the Map*, in enabling communities to adapt and sustain digital tools for their own purposes. This will lead into a broader exploration of scaling down complexity in technological design, showcasing speculative projects like *Windternet* and practical examples like *Collapse OS* and *Low-Tech Magazine's* solar-powered website, which prioritise resilience, sustainability, and adaptability to local contexts over traditional metrics like performance or scalability.

This section will culminate in a discussion of how embracing relational and responsive forms of agency, as proposed by Bridle ("An Ecological Technology"), can guide us toward more ethical and reciprocal technological practices that move beyond control and domination, fostering coexistence with the complex systems we inhabit.

Rationale

This thesis is not a critique on a specific piece of technology, but rather on the anthropocentric values that inform how large corporations *make* technology and permeate through their tools. In seeking alternative, more fungal practices of thinking and making technology, it sees in software a potential for liberation from extractive and domineering logics, as exemplified by the many projects discussed in Part II. That being said, it does not pretend that the ongoing climate crisis, or the myriad of socio-economic issues arising from ecological injustices, can be "solved" by technological means alone. Neither does it suppose that technology alone is at the source of such fundamental and complex issues. Distancing itself from any techno-utopian/-dystopian binaries, this thesis seeks to provide a nuanced reflection on the ecological and material entanglements of technological systems and the thinking that informs them.

Such a reflection does not aim to determine any single solution to the issues at hand, nor could it possibly do so, as both the effort to live within a materially finite ecosystem and the production of technology are ongoing, multifaceted and deeply complex processes. Instead, this thesis aims to contribute to a foundational shift in how we think about and engage with technology, beginning with an ecological criticality that challenges the extractive and domineering logics underpinning mainstream technological practices. It is not driven by the grandiose ambition of solving the climate crisis but rather by the humbler, yet equally urgent, goal of laying the groundwork for dispelling the myth of human supremacy which is so deeply woven into technology.

This work is necessarily shaped by its immediate context. Much of the academic research, activist projects, and examples it draws upon are rooted in the Netherlands or Central Europe and reflect predominantly Western intellectual traditions. This reflects the knowledge and resources I have had access to during this research process.

However, I acknowledge that this perspective is far from universal. Many of the ecological and relational insights this thesis foregrounds resonate with, and are deeply enriched by, indigenous and non-Western forms of knowledge that often remain outside the scope of Western academia (Celermajer et al 7-9). While this thesis does not directly engage with these knowledge systems due to the limits of my expertise, time and context, I recognise their value and necessity in global conversations about ecological and technological justice.

By engaging critically with the material and cultural logics of Western technological systems, this thesis seeks to provide a modest contribution to a much larger, plural and ongoing dialogue about how we might imagine and foster more ecologically sustainable and interconnected futures.

As this thesis focuses primarily on processes of making rather than their end-products, its approach to gathering knowledge must reflect the embodied nature of this practice, which combines theory and practice.[2] To reflect this interplay, this thesis draws significantly from theoretical analysis but seeks to ground and activate this knowledge through practical examples. In doing so, it reframes theory and practice as an intertwined process. By engaging with the work of non-academic collectives such as permacomputing and Radical Data, it incorporates activistic, self-organised, and bottom-up ways of knowing that are often excluded from the canon of Western academia. This intentional inclusion modestly highlights the value of non-codified knowledge systems and positions them as integral to rethinking how we make and relate to technology. Dissatisfied with the industry's response to the climate crisis, primarily framed through "green capitalism" and solutionism, I approach this thesis not as a critique of technology itself but of the processes and values underlying how it is built.

[2] In his analysis of the Homeric hymn to Hephaestus (Hesiod 446), Richard Sennett describes the craftspeople it honours as “those who combined head and hand” (22). Contrary to negative stereotypes brought about by the industrial revolution, which saw a devaluation of the craftsperson and a separation of the making process into managerial and labor roles, making is neither purely physical nor purely intellectual. Instead, it is a critical, embodied process that weaves together mind and body.

Part I. More-than-human Intelligences
And Why We Should Listen to Them

1. Anthropocentrism in the Technology Industry and the Climate Crisis

Sing, clear-voiced Muse, of Hephaestus famed for inventions. With bright-eyed Athena he taught men glorious crafts throughout the world, —men who before used to dwell in caves in the mountains like wild beasts.

– Hesiod, Homeric Hymn to Hephaestus (446)

In *Wild Mind, Wild Earth*, David Hinton links the ongoing climate crisis to a dualism between humanity and nature (6), which he traces to technological shifts in civilisation. The shift from hunter-gatherer to agrarian societies created a separate space for humans within their broader ecosystem, where “nature” could be controlled by means of domesticated plants and animals. This shift, Hinton argues, brought forth a more detached, instrumentalist relationship with the material world, reducing it to something to be overcome. Later, the invention of writing created a conceptual separation between the human mind, which became thought of as permanent and immaterial, and the physical world, experienced only in the present (64-65). *The tools that we used to create civilisation, thus led to a devaluation of the material world.* This subjective mental realm was conceptualised by Greek-Christian myths as the soul, an immaterial identity-centre unique to humans (66-68). The *Book of Genesis*, foundational to both Christian and Jewish religions, took this divide further, depicting a world created for human dominion[3] (White 1206).

Hinton’s arguments underline that making technology is not a purely functional endeavour. Technology has the power to shape the world according to the desires and biases of its makers, influencing how society collectively understands and engages with the world. The same holds true for contemporary society. Through a critique of modern corporate practices, Bridle warns that when the responsibility of building technology is entirely delegated to corporations, their anthropocentric, extractive and profit-driven

[3] This perspective is influenced by historian Lynn White who, in 1967, traces the ecological crisis to the Western Christian paradigm, which he calls the world’s most anthropocentric religion. White points out that according to the Christian creation myth, God created Adam, the first man, in his shape. Everything else, including Eve and all the animals, was created to serve man’s purposes. In extreme contrast to ancient paganism, which it actively suppressed, Christianity opposes animism – the attribution of a spiritual essence to places, objects and all living creatures – making it possible to exploit the material world without any moral qualms, as it is God’s will (1206).

values become embedded in society, shaping the perspectives of present and future generations (*Ways of Being* 10).

The longer these values go unquestioned, the more embedded they become in societal norms, leading us – broader society, which relies on corporate technological systems – to replicate and embody them. This manifests in practices such as exploiting fragile ecosystems to mine the minerals that power modern computation (Crawford 15), using artificial intelligence and machine-learning platforms to accelerate fossil-fuel extraction – the leading cause of climate change (Bridle, *Ways of Being* 6) – and consuming vast amounts of water and electricity to cool data centres, the material infrastructures behind the metaphorical "Cloud" (Bridle, *New Dark Age* 68). These actions not only perpetuate harm but also normalise a worldview prioritising profit and extraction over ecological reciprocity, leading to ecological degradation that threatens all life, including our own.

A present-day example of anthropocentric corporate values shaping public opinion is the ongoing cultural obsession with artificial intelligence (AI). A rapidly expanding field, AI is now deployed at a large scale by a small number of powerful corporations, and their systems are seen as a proxy for the human mind (Crawford 4-6), framing intelligence as a uniquely human capacity. This perpetuates the problematic myth of human supremacy, excluding non-human intelligences – such as ecosystems, fungi, and other dynamic, living processes – which are all around us, yet have been devalued by Western systems of knowledge.

Research into the most established companies developing AI reveals the field's limited view of intelligence as well as the interests this intelligence serves. Google ("What is AI?") and IBM (Stryker and Kavlakoglu) explicitly define AI as simulating human intelligence. OpenAI takes a more expansive approach, defining artificial general intelligence (AGI) as "systems that are generally smarter than humans" and going on to claim they want AGI to "empower humanity to maximally flourish in the universe," which it could do by "increasing abundance" and "turbocharging the global economy" (Altman). While it vaguely hints at a broader understanding of intelligence, the latter definition fails to elaborate meaningfully. Instead, it makes ambiguous claims about the utopian future it promises,[4] rooted in a fictitious rhetoric of abundance, domination and human supremacy, which is in direct opposition with the post-growth paradigm I will argue for in Part II.

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[4] Sam Altman would likely disagree with my analysis of his views on a future shaped by AGI, which he claims are not utopian. This thesis does not oppose a nuanced discussion of AI, or AGI, as a technological field with emancipatory or ecologically regenerative potential. However, I argue that the grandiose claims about the benefits of AGI in his text paint an idea of progress rooted in human supremacy and abundance which is not sustainable in a materially finite planet. This will be elaborated on further in Part II of this thesis, when discussing post-growth paradigms and computing within limits.

Bridle argues that by expanding our perception of intelligence beyond the human mind, we can “break down some of the barriers and false hierarchies that separate us from other species and the world,” fostering “new relationships based on mutual recognition and respect” (*Ways of Being* 14). These relationships are not about rejecting technology or reverting to hunter-gathering, but about cultivating perspectives that value multi-species interdependence and ecological balance – factors that are largely ignored by our current techno-cultural systems, often with destructive consequences. Incorporating fungal learnings in software development methodologies, as I explore in this thesis, is one step towards developing this ecological mindset. It is not an end-goal but a process through which we can begin to cultivate an ecological thought that will permeate our ways of building, using and relating to technology.

2. Fungal Teachings in Systems Thinking

Systemic literacy is a crucial competency to comprehend technological systems – not just their computational mechanisms, but also their histories, contexts, and material and social consequences (Bridle, *New Dark Age* 8-9). Can the study of fungi as ecological connectors help cultivate the systemic awareness necessary for a more thoughtful engagement with technology? To address this hypothesis, I will start by exploring how fungi can contribute to a new form of ecological systemic thinking (2a), after which I will focus on the concept of regenerative interfaces (2b) as a mechanism that can be transported to the world of software development.

2a. Fungi as a Model for Systemic Literacy

Fungi are everywhere, yet they are mostly invisible. Most of their activity takes place underground, in vast and complex fungal networks, hidden from the naked eye. These networks model an interconnected, relational perspective that could urge us to see beyond isolated tools and processes to the wider systems they inhabit and shape. To study fungal networks, mycologists often rely on a systemic approach, analysing entire ecosystems for signs of fungal activity. They examine carbon fluxes, plant and soil health, and the symbiotic relationships that fungi form with other organisms. Sheldrake notes that understanding ecosystems requires shifting focus from individual species to the relationships that sustain them, with fungi often playing a central, connective role (*Entangled Life* 18).

Advancements in molecular techniques in recent decades have allowed researchers to observe previously invisible fungi communities, unveiling their diversity and ecological roles.[5] Bruns contends that fungal systems are not just contributors to existing ecological frameworks but are actively reshaping community ecology theory, prompting the development of more inclusive ecological frameworks (396).

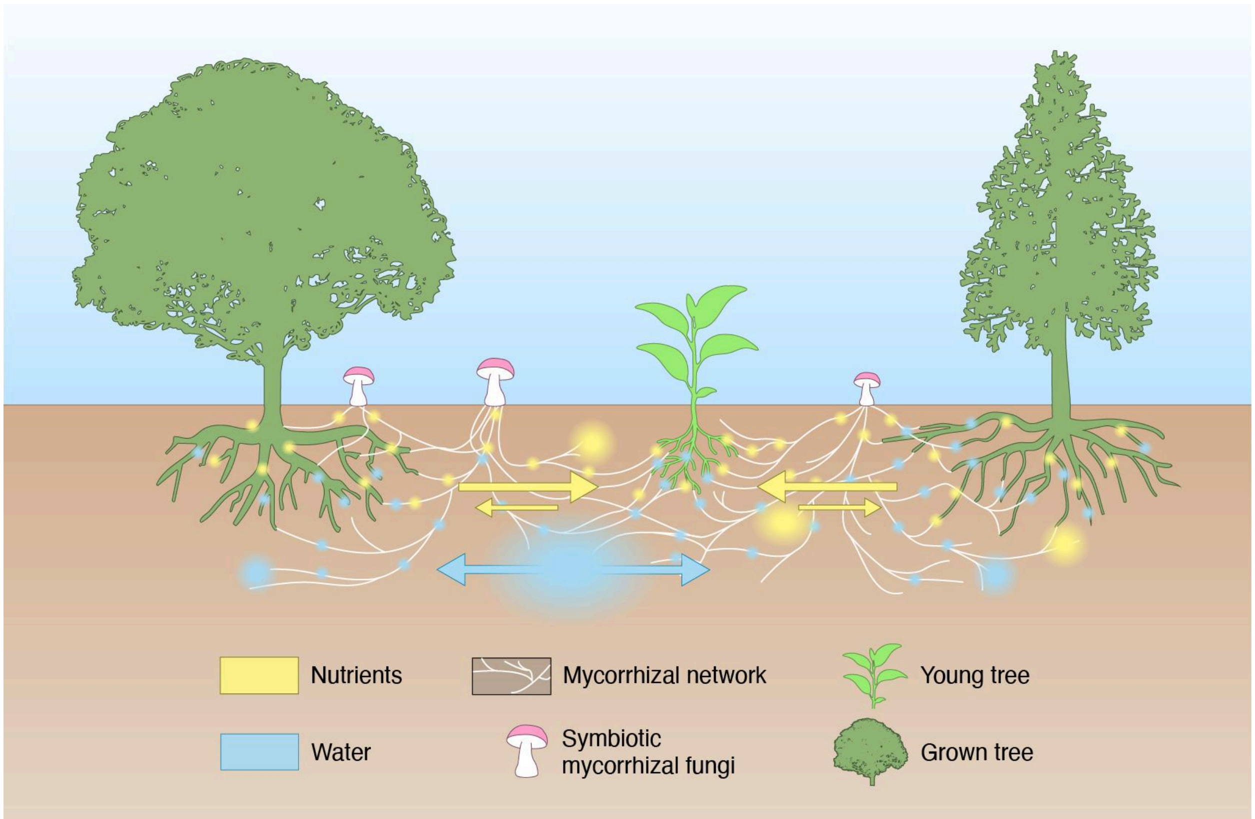

Figure 1. Distribution of water and nutrients between trees across a shared mycorrhizal network.

As a result of their ecological significance, which fuelled mycological research, fungi have also become widely discussed in the humanities. The relational principles observed in fungal networks offer a fertile ground for rethinking human systems and philosophies, as demonstrated by three key texts informing this thesis. Anna Tsing's *The Mushroom at the End of the World* examines the matsutake mushroom as a lens to explore interdependent systems in precarious landscapes, highlighting how fungi challenge individualistic and linear thinking. Yasmine Ostendorf-Rodríguez's *Let's Become Fungal* calls for a shift in human systems design by adopting fungal principles such as mutualism, distributed agency and self-organisation. Merlin Sheldrake's

[5] Historically overlooked due to their microscopic nature, fungi were underrepresented in community ecology (Bruns 393) as well as biology (Sheldrake, *Entangled Life* 182), both fields predominantly centred around plants and animals.

Entangled Life depicts fungi as metaphors for relationality and interconnectedness, arguing for their potential to reshape our understanding of life itself as an inherently collective and connected experience.

Fungi's ecological and philosophical relevance underscores their potential as a model of reciprocal and dynamic relationships that nurtures broader systemic thinking across disciplines. *Let's Become Fungal*, in particular, not only contributes to the growing humanities discourse on fungi but also offers insights into systems thinking. Through gathering underrepresented[6] and ecologically-focused knowledge about fungi, it seeks "a mutually beneficial system design for humanity, seen through a mycological lens" (7), tying back fungal behaviours in self-organisation (80-90) and distributed agency (261-263) to systems thinking. In her exploration of fungi as a model for mutualistic, self-organising systems, Ostendorf-Rodríguez challenges traditional control-oriented models, bridging the study of fungi and systemic thinking in ways that resonate with third-wave cybernetic principles, particularly those of posthumanist and new-materialist thought.[7]

She argues that fungi can teach us to live with uncertainty, a lesson embodied by her searches for rare mushrooms whose distribution is unpredictable. Abandoning set expectations and embracing the unknown challenges the human desire for control, which is deeply ingrained in our technological systems. This aligns with the posthumanist and new-materialist goal of decentering the human and recognising agency in complex, more-than-human systems (254-269).

Another lesson fungi offer is their resistance to categorisation, with extreme fluidity in their "genders," sexuality and modes of organisation. Instead of overly fixating on individual traits or taxonomies – such as trying to categorise mushrooms that do not fit established labels – fungi encourage us to focus on the relational dynamics between species. This is a key principle of systems thinking and cybernetics, where the emphasis is on networks of interaction rather than individual elements (168-182).

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[6] Ostendorf-Rodriguez has conducted extensive research into fungi in South America, through contact with Latin women and non-binary mycologists, artists, small-scale farming collectives and indigenous communities.

[7] The field of cybernetics, which is a key part of general systems theory, draws theoretical parallels between biological and technological systems. Third-wave cybernetics takes this further, by moving away from the control-oriented approach of earlier cybernetics work, toward emergent, self-organising and distributed agency systems. This has influenced posthumanist and new materialist discourse, supporting the ideas of decentering the human, acknowledging the agency of non-human species and challenging dualisms towards an entangled view of human, more-than-human and technological systems.

Finally, fungi, as natural decomposers, challenge the linear understanding of life and death. By breaking down dead matter, they transform it into new life, illustrating the cyclical nature of existence. This mirrors the cybernetic concept of feedback loops, where decay and transformation are integral to growth. In the context of software development, this suggests a shift toward designing systems that acknowledge their potential for decay and transformation in the face of obsolescence, asking how software and its supporting infrastructure will age, decompose and evolve. Can we create non-linear technology that continues to mutate through cycles of change, rather than being discarded? As Ostendorf-Rodríguez puts it, "transformation is the best conservation" (96-113).

In arguing for a more systemic approach to understanding technology and its ecological entanglements, I want to proceed with caution by pointing out its potential limitations. By focusing on relational dynamics, systemic approaches risk overlooking the specificity and nuance of individual components within a system. Additionally, the complexity of systemic thinking can be overwhelming, making it difficult to translate abstract insights into actionable strategies. Nevertheless, I am advocating for a more systemic and relational understanding of technology within its broader ecological contexts, as I believe this type of thinking is lacking, particularly in the technology industry. Current responses to the climate crisis tend to isolate and reduce it into discrete, "solvable" problems, ignoring their deeper, interconnected root causes, as I will expand on in Part II. A systemic approach has the potential to address these oversights by creating relational awareness.

Throughout this thesis, I will draw on systemic thinking, particularly from posthumanist and new-materialist strategies which help us engage with the cybernetic system we all inhabit. By using fungi as both metaphor and inspiration, I aim to show how these theories move beyond abstraction, embodying a more-than-human approach to understanding systems by grounding my exploration in a living, ecological model.

2b. Mycorrhizal Fungi: Towards a Regenerative Interface

“Technology is the active human interface with the material world.”

– Ursula K. Le Guin*, A Rant About “Technology”*

When accused of avoiding technology in her work, the feminist science-fiction writer Ursula K. Le Guin proposed her own definition of the term (“A Rant About ‘Technology’”). The latest, most powerful computer, just like a paperclip or a pair of shoes, are all considered technological by Le Guin, as they are tools humans use to interact with the physical world. Her framing invites us to consider technology as deeply embedded in the human condition, not as an external force or a modern invention, but as a continuous thread running through human history. By looking at technology as a socio-natural process rather than a purely technical construct, Le Guin's work engages with technology as a means to understand how minds, societies and cultures work.

Moreover, by including something as mundane as shoes under the umbrella of technology, Le Guin critiques the modern obsession with enormously complex and specialised technologies, which she claims are "supported by massive exploitation both of natural and human resources." Her expansive definition reclaims the term, redirecting attention from the spectacle of "hi-tech" innovation to the lived, everyday human experiences that rely on "low" forms of technology, often taken for granted. This democratisation of technology challenges technocentric narratives that prioritise efficiency and computational power over ecological and social values.

In summary, Le Guin's conception of technology is both humanistic and ecological. It acknowledges that every tool, from the most rudimentary to the most advanced, is an interface which mediates our interactions with the material world, shaping how we understand our place in that world.

This understanding of technology as an interface opens up interesting parallels beyond the human realm. Mycorrhizal fungi function as a kind of ecological technology, allowing environmental scientists to understand the underlying dynamics of forest ecosystems, including how nutrients, water and chemical signals are exchanged between plants through mycorrhizal networks. In the 1980s and 90s, research showing that carbon could pass naturally between trees that shared a mycorrhizal network, contributing to sustain plant health across the entire network, challenged how the scientific community understood plant life, suggesting it might not be appropriate to think of plants as neatly separable units (Sheldrake, *Entangled Life* 156-157). This led to the term "Wood Wide Web," a play on "World Wide Web" to describe mycorrhizal networks – underground systems, or mycelial interfaces, one could say – formed by mycelium that connect plant roots to nutrients (Stamets 5).

Sheldrake points out the similarities between the "Wood Wide Web" and the "World Wide Web" by noting how both function as complex, interconnected networks that share fundamental principles. Just as a 1998 project to map the "World Wide Web" revealed its resemblance to ecological and biological systems, the "Wood Wide Web" works on comparable principles of resilience, interdependence and information exchange that can be studied by network science (*Entangled Life* 157-158). This comparison is supported by mycologist Paul Stamets, who described mycelium as "nature's internet" (13).

The “Wood Wide Web” metaphor not only underscores the impact of this scientific discovery – reshaping how we understand forests as cooperative rather than competitive ecosystems, an idea I will elaborate on in Part II – but also serves as a conceptual bridge between ecological and technological systems. Like the technological interfaces described by Le Guin, mycelial interfaces facilitate interaction and flow within complex systems, but they do so in a way that nurtures and sustains the systems they connect. By distributing nutrients across ecosystems, mycorrhizal fungi are now considered one of the most ecologically important soil organisms in both natural and managed environments (Hawkins et al. 560), giving them a significant role in ecologically restorative practices,[8] such as permaculture. Viewing mycorrhizal fungi as mycelial interfaces raises an interesting question: can alternative technological interfaces that adopt mycorrhizal principles become regenerative rather than extractive towards the systems they are a part of?

Permaculture is an alternative approach to industrial farming based on the ethical principle of “working with, rather than against nature.” As a design system, permaculture draws its fundamental principles from systems thinking, casting a holistic view on human and more-than-human agents (Mollison et al. 1). Comparably to how permaculture challenges industrial agriculture, the *permacomputing* community challenges environmental and social challenges in today’s computer and network technology. Defining themselves as both a concept and a practice-oriented community, permacomputing organise meetups, workshops and discussion groups (“Community”) to collectively and radically rethink computational culture around issues of resilience and regenerativity (“Permacomputing”). Software projects that align with the concept of permacomputing are not definitive technological answers to ecological issues, but rather ongoing, technical attempts at addressing them through collaborative means. These projects deal with issues such as digital degrowth, autonomy from extractive energy sources, low-bandwidth and low-complexity systems, digital resilience and promoting systemic literacy over technological systems (“Projects”).

We have explored how fungal networks, as ecological connectors, offer a compelling model for cultivating systemic awareness in technology. By examining their relational dynamics, we uncover lessons in interdependence, adaptability and mutualism that challenge linear, control-oriented approaches embedded in technological paradigms. The study of fungi not only offers a shift in perspective – from isolated tools to the broader systems they inhabit – but also inspires the concept of regenerative interfaces,

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[8] The elaborate ways in which fungi contribute to ecological restoration is beyond the scope of my thesis, but I point readers to Stamets’ chapter on mycorestoration (106-249).

which prioritise resilience and circularity over extraction and obsolescence. This systemic lens, informed by fungal principles, lays the groundwork for rethinking how technology can actively contribute to the flourishing of interconnected systems. As we move forward, I will elaborate on projects and communities affiliated with permacomputing, such as CollapseOS and LIMITS, illustrating how the fungal principles discussed here can inform software development methodologies, bridging theory with practice.

Part II. Making Better, Together

Collectivising Access to Tools, Letting Go of Tech Solutionism and Embracing Collaboration in Place of Competition

1. Open-Source Communities and Mycelial Networks: Lessons in Decentralising Power

Fungi are decentralised organisms. A mycelial network has no "brain," no command centre. Control is dispersed across the many nodes that compose a network. This decentralised structure gives fungi – and the numerous plant species that depend on them – their resilience. The common idiom "cut off the head of the snake and the body will follow" falls short when there is no head to cut. A single fragment of mycelium, Sheldrake explains, can regenerate an entire network (*Entangled Life* 56). Through rerouting resources around damaged areas, mycelia remain adaptable in the face of disruption, maintaining the overall health of their ecosystem.

This decentralised structure is not unique to fungi – it mirrors the organisation of open-source software. Both systems thrive on collaboration, interdependence and adaptability, enabling them to maintain their integrity in the face of disruption. Open-source software relies on contributions from a community of developers. The lack of a centralised controller allows anyone to contribute to or iterate on a project, opening up multiple pathways for improvement and maintenance. Eric Raymond describes the Linux operating system as following the "bazaar" model of collaboration, where a piece of software is continuously worked on by a large group of people in a worldwide code-writing "bazaar" (21-22). Such a model allows for fast problem-solving, the sustaining of diverse needs (via the different Linux distributions) and reduces the risk of single-point failures. Much like mycelium, if one contributor or a piece of Linux code fails, others will almost immediately step in to replace it.

Critics of Raymond's bazaar model point out coordination and quality-control challenges as open-source projects upscale (Kamp 20-21). Having acknowledged this, it is important to question if scale should be used as a benchmark to dismiss decentralised open-source projects as a whole. Open-source projects rooted in bottom-up, DIY and activist settings offer powerful counter-narratives to centralised technological systems, as I will expand on in point 3. "Survival of the Commons." While scaling up can prove challenging for decentralised architectures, these concerns are more pertinent in commercial contexts, due to economic concerns, large user bases and competitive pressures. In contrast, community-driven projects prioritise experimentation and adaptability to local needs, which are not immediately concerned with scale. I argue that addressing scale too early risks gatekeeping innovation by imposing metrics rooted in commercial success onto radically different contexts. For the time being, we must embrace the messiness and iterative growth of new ideas. The challenges of scale, if relevant, can be addressed at a later step, once these transformative approaches to technology have had the chance to establish themselves and evolve.

A more pressing challenge lies in open-source systems' ability to create truly inclusive ecosystems, extending their benefits beyond developer communities. While open-source communities have made significant strides in democratising access to technology and creating decentralised, resilient models, this approach has its limitations. Their focus often remains narrowly on the needs and agency of programmers, sidelining broader communities, such as non-technical users and ecological stakeholders affected by digital systems. In contrast, mycelial networks benefit entire ecosystems, forming collaborative relationships with different plant species, each of which relies on the network for signalling and resources (Sheldrake, *Entangled Life* 17). This inclusive structure allows the mycelium to support the health and resilience of diverse organisms across the ecosystem they are part of.

Open-source projects might draw inspiration from this interspecies collaboration by finding ways to address the needs of broader agents, human and beyond, affected by their work, developing more inclusive approaches to decentralisation. Embracing this model would mean going beyond development-driven decision making and extending agency to non-programmers and ecological stakeholders, creating a collaborative ecosystem that considers the social and environmental impact of digital technologies in a more inclusive way.

1a. Radical Data: Extending Agency Through Participatory Design

Radical Data (RD) is a multidisciplinary collective of mathematicians, technologists, dancers and designers focused on research and development of digital tools designed around the principles of joy and liberation. Based in the Netherlands, they run workshops worldwide aimed at empowering activists and local communities to “use technology as a tool to shape the world” according to their own often underrepresented needs (“Radical Data”).

RD reflects the principles of decentralisation and collaboration by rethinking traditional power structures in technology development, prioritising inclusivity and community-driven values over top-down control. They decentralise not only technological decision-making but also the types of knowledge and experiences that shape digital tools. I asked them how they empower people through their software practices, and how might that agency be extended beyond programmers.

RD described how, in working with non-technical communities, they found that people can contribute to and have ideas around technology independently of their technical knowledge. This has shaped their workshops towards a re-centring of different types of knowledge, often stemming from lived experience and cultural insights.

These workshops function as spaces for dialogue, discussion and collaboration around technology and are divided into three phases: Dissect, Imagine and Create. During the “Dissect” phase, participants critically examine existing technologies, collectively uncovering the socio-political values embedded in them. The “Imagine” phase invites creative ideation, making use of speculative design to envision alternative systems rooted in community values. During “Create,” RD translates these ideas into prototypes, iterating on them with participant feedback. Here, RD minimises technical barriers by taking responsibility for the coding itself, while enabling non-technical contributors to shape the project’s conceptual and functional direction.

RD’s participatory design workshops illustrate how decentralisation can transcend technical boundaries, empowering communities by incorporating diverse perspectives into the development of digital tools. Their work serves as a practical example of how decentralised principles, such as shared agency, inclusive knowledge systems and non-hierarchical collaboration, can be implemented in a real-world context.

Participatory design approaches such as this have been widely researched and practiced across disciplines and can inform inclusive methodologies, including the extension of agency beyond technical users in open-source communities. While the participatory methods discussed here have largely focused on human agents, the potential to broaden this framework to include more-than-human actors, such as ecological systems and other non-human entities, is a necessary next step. However, this decentralisation of power must start somewhere, and addressing the immediate needs of diverse human communities is a foundational step.

Moreover, the intentionality underlying participatory design processes is critical. Whether such initiatives are driven by liberatory goals – centering social and ecological justice and community empowerment – or by corporate motives, the forces behind participatory design will always influence its outcomes. Comparable participatory methods are also employed by companies to leverage user feedback mechanisms for targeted marketing and market expansion. As we embrace participatory design to challenge centralised technological systems, it is essential to be critically aware of who is behind these efforts and to ensure that they are aligned with transformative goals rather than serving the already established power structures.

Infusing ecological thought into participatory design methodologies would require actively engaging with ecological systems and other non-human entities as stakeholders in technological development. Such an engagement is not bound solely to the fields of software development or technology but could be deeply enriched by the emerging field of multi-species justice, particularly in the context of deliberation and representation, as discussed by Celermajer et al. (13-14). For instance, open-source projects could incorporate principles of ecological reciprocity directly into their design processes, as will be exemplified by projects further on (3. Survival of the Commons). This more-than-human perspective represents a crucial next step in our understanding of decentralised systems.

However, achieving such a shift will require deep, systemic change – a reorientation of technology away from anthropocentric values and toward a broader, ecological consciousness. This willingness to embrace systemic transformation is often hindered by technological solutionism, which frames the ecological crisis as a series of isolated problems solvable through discrete technical fixes. The next section will explore how dismantling the culturally ingrained reliance on techno-fixes can enable a shift towards a digital post-growth paradigm, one that prioritises ecological regeneration and systemic justice over the relentless pursuit of growth.

2. The Post-Growth Shift: Being Open for Systemic Change and Resisting the Allure of Single-issue “Tecno-fixes”

The information and communications technology (ICT) industry has long been driven by principles of perpetual growth, often operating under the assumption that “more is better” and resources are limitless. These assumptions underpin many of today’s harmful computing practices, as highlighted by the permacomputing community, which critiques these growth-driven paradigms and calls for a deeper reckoning with the ecological impacts of technology (“Issues”). Adopting a post-growth approach to technology directly challenges this growth-centric model, yet doing so requires we deconstruct the technological solutionism that has become culturally internalised through an over-reliance in, and purely functional understanding of, technological systems (Bridle, *New Dark Age* 8-9).

Post-growth represents a social and economic stance that proposes to deprioritise the dominant paradigm of quantitative economic expansion in favour of qualitative development, particularly in the context of social well-being, economic justice and environmental regeneration. It acknowledges that, on a materially finite ecosystem, extractive economies cannot grow infinitely (Daly 1).

Soper argues for post-growth living as an ecological necessity in light of the ongoing climate crisis (8). Soper’s thinking challenges the capitalist narrative that human progress and well-being is tied to economic or technological growth. She describes technological “quick-fix solutions” to climate issues within the current framework of so-called progress as means to keep labour and consumer spending on course, which get in the way of a much needed alternative model of progress (9). In support of this view, Haraway (3) stresses her intention to dispel the “comic faith in tecno-fixes” that she considers an inadequate response to the environmentally disastrous effects of the Anthropocene[9].

[9] Both Soper (8) and Haraway (3) acknowledge that there is value in situated technological interventions, although not in isolation or in place of a radical change in how we approach consumerism. Whereas both their work engages with post-consumerism and post-growth, Haraway decentres the human, an approach which Soper criticises. In sum, Soper defends the necessity of maintaining distinctions between humans and other entities, not to assert dominance, but to responsibly address humanity’s distinct agency over the material world as well as our unique position to extend moral consideration to other species (17-21). Despite these differences, their critiques of technological quick-fixes and their advocacy for systemic change highlight points of alignment, making their perspectives complementary in the broader discussion against technological solutionism.

At the time of writing, one can see photographs (Vucci) of the newly appointed leader of the US Department of Government Efficiency, Elon Musk (Wen), sporting an “occupy Mars” t-shirt beside a re-elected Donald Trump. The SpaceX Mars colonisation program, described as “dangerous and ridiculously expensive” (Wattles), perpetuates the colonialist ideology of seeing distant land as a resource to be exploited and supports the argument of giving up on our already damaged planet. Getting such visibility on a world stage perfectly illustrates how the danger of tech solutionism does not lie only in the material consumption of the technology itself, but also in how it shapes public opinion. Relying on an unsubstantiated faith in technology distracts us from the structural changes needed to address the climate crisis and diverts important resources from simpler, community-led solutions that prioritise ecological balance and social justice.

On not-so-distant land from where I am writing this thesis, off the North Sea coast, Shell is spending large amounts of money from public funding (“Carbon Capture’s Publicly Funded Failure”) in Carbon Capture and Storage (CCS) technologies, a process which mycorrhizal fungi do naturally.[10] CCS promises to capture CO_2 emissions from industrial processes and store them underground (“Carbon capture and storage”), offering a techno-fix for climate change without requiring fundamental changes to fossil fuel industries. This technology is expensive, energy intensive and unproven at scale[11] (Race). CCS can work against systemic transitions to renewable energy by allowing fossil fuel companies to continue operations under the guise of "carbon neutrality." This diverts resources and attention from strategies such as reducing consumption, energy efficiency, and equitable renewable energy deployment, which address more directly the root causes of climate change.

Technological solutionism – the belief that technology alone can solve complex environmental or social issues – oversimplifies systemic problems and obstructs genuine ecological justice. Besides taking up resources that could otherwise be invested in fostering real, systemic change in how we produce and consume technology, as seen above, it also lulls us into what Bridle calls computational thinking. This type of thinking, Bridle argues, is the internalisation of solutionism to the degree

[10] An estimated 13.12 gigatons of CO2 is, at least temporarily, allocated from terrestrial plants to the underground mycelium of mycorrhizal fungi each year, confirming mycorrhizal associations’ significant contribution to global carbon dynamics (Hawkins et al. 560). This equates to 36 percent of our yearly global fossil fuel emissions, making mycorrhizal fungi arguably more efficient carbon captors than any CCS unit in the world.

[11] Unlike community-driven projects that should prioritise experimentation, CCS is a corporate initiative heavily backed by public funding and designed to operate at industrial scales. In this context, scalability is not a secondary developmental concern but a fundamental expectation, and the failure to deliver at scale highlights the limitations of this techno-fix.

that it becomes “impossible to think or articulate the world in terms that are not computable” (*New Dark Age* 9).

Resisting the allure of tecno-fixes becomes therefore a necessary first step towards a digital post-growth. How can we cultivate a healthy level of scepticism, rightfully valuing situated technological projects[12] and the people who develop them (Haraway 3), yet seeing through large corporations’ attempts at greenwashing us?

Bridle traces solutionist thinking back to the limited scope of technological education, which overemphasises a purely functional understanding of the systems it deals with (*New Dark Age* 8-9). Even as makers and programmers, we often find it hard to visualise and understand the true impact of new technologies, making it difficult to develop the much needed systemic literacy described earlier. Addressing this gap, Bridle argues that what is needed is not new technology, but better ways to describe it – new metaphors to make sense of the complex systems shaping our world (*New Dark Age* 10, 18).

Once again, I propose we look towards the world of fungi, experts in fostering symbiotic relationships by regulating and distributing finite resources within their ecosystems, for these metaphors. In *Entangled Life,* Sheldrake describes fungi as mediators of interactions between plants (165). They achieve this through a deep awareness of their environment. Guided by chemical signals in the soil, fungi branch out their hyphae (tube-like structures) towards each other as well as receptive plant roots which they fuse with, becoming a mycelial network (13, 42-43). The hyphae allow mycelial networks to transport nutrients and water over large distances based on environmental needs (61). For instance, a fungus can selectively allocate nutrients, supporting weaker seedlings (see fig.1) which, in turn, will supply it with carbon once they grow larger (165). Fungi invest their resources in maintaining symbiotic partnerships with plants and insects which ultimately support their own reproduction, a survival strategy that prioritises the health of an entire system.

[12] Nothing in this thesis is an argument against technology. If we accept Le Guin’s broad definition of technology as the “active human interface with the material world,” arguing against technology would be to argue against a future where humans are able to coexist with the material world less destructively. Rather, this thesis chooses to remain optimistic towards its main argument: that we can foster a more thoughtful and ecologically sound relationship with technology.

3. Survival of the Commons

In the face of ecological crises, humanity's long-term well-being and survival is intrinsically tied to the health and survival of the *commons* – shared systems that sustain life on Earth. These commons include not only material systems such as air, water and soil, but also intangible systems such as cultures, knowledge and cooperative relationships. The survival of the commons demands a departure from tech-solutionism, which neglects the broader ecological and social systems that software impacts and depends upon. It calls for a systemic approach to building software collaboratively that is rooted in contextual awareness, respects ecological limits and scale, and operates with a considerable level of autonomy from extractive technological systems.

By drawing from metaphors found in mycelial networks, which seek survival through the health of their ecosystems, we can envision methods of creating software that support and sustain shared ecosystems. Just as fungi mediate interactions and redistribute nutrients to ensure the resilience of their environments, developers must cultivate practices that prioritise the long-term health of digital and ecological commons. This section explores how adopting these metaphors can help software developers align with ecological principles, fostering systems rooted in collaborative frameworks that can repair our bond with – rather than further abstract us from – the living world.

3a. Contextual Awareness

Collaborative practices capable of supporting the commons must be rooted in a nuanced understanding of the entanglements between digital and material systems and of the ecological limits within which ecologically-minded computing practices must operate.

Fungi exemplify a profound ecological literacy, operating with an acute sensitivity to their surroundings. This awareness allows them to perform their role of ecological regulators, as described above. A similar systemic literacy can be applied to software development through an expanded understanding of dependencies, fostering a shift from purely functional optimisation to a holistic ecological perspective.

In software development, dependency mapping – the practice of tracing the interconnections between software, libraries and infrastructure – is a common technical process. However, it is often driven by functional goals, such as improving efficiency or managing vulnerabilities ("Benefits of dependency mapping"). Inspired by the mycelial model, I argue that dependency mapping should be reframed as an ecological and social inquiry. This involves examining the environmental and social implications of each dependency, recognising the complex networks in which software is embedded.

Beyond informing an impact assessment, this process must integrate a collective governance model, reflecting the diverse perspectives and needs of impacted human and more-than-human communities. Just as fungi distribute “their” resources to maintain overall ecological balance, developers must invite collaborative decision-making that prioritises the health of the commons, even if that decreases their individual agency over the software. Framing practices of dependency mapping within an ecological framework embeds software development within its material and environmental contexts, contributing to the ecological turn in technology as explained by Bridle, who considers such a shift essential for situating technology within the networks of life it ultimately depends upon (*Ways of Being* 11-14).

To ground this ecologically-focused approach to dependency mapping in practice, consider the following line of inquiry:

- What systems does my software rely on?
- Who or what might be harmed by these systems?
- Who profits from these systems? What are their interests or values?
- If their interests do not align with the software I want to build, what alternatives are there? (Consider open-source alternatives.)
- Are there simpler or low-tech ways around such dependencies? How can my software operate within the material and ecological limits of its environment?

These questions embody a shift from functional optimisation to ecological and social accountability. By interrogating dependencies in such a way, developers can address not only the technical implications of their choices but also their environmental and social ripple effects.

<u>3b. Understanding Limits and Scale</u>

A deeper interrogation of these dependencies is unlikely to produce more computationally efficient systems in the conventional sense. Instead, it favours simpler, lower-complexity designs that prioritise a lower energy consumption and maintenance cost over scale and performance, fostering technical projects that emerge from and serve local communities. Such projects, by remaining relatively independent from global chains of production, reflect a bottom-up ethos that aligns software development with the realities of our planetary limits, mirroring the resilience of fungi in adapting to the limits of their environment.

As natural decomposers of dead matter, fungi often thrive in damaged environments. The matsutake mushroom in particular has been known to grow in landscapes affected by human disturbance.[13] Tsing frames the matsutake as a model for coexistence within environmental disturbance and the resulting (ecological, social and economic) precarity, taking up the stories of precarious livelihoods and environments through tracking matsutake commerce and ecology (3-4). Can we too, as makers of digital tools, work from the knowledge that we live in a damaged environment? Can we, like matsutakes, thrive in it without further damaging it?

Matsutake's resilience in the face of precarity offers a compelling metaphor for rethinking computing within ecological limits. Such an approach is being developed by LIMITS, a multidisciplinary community of researchers from fields such as computer science, engineering, information science, social science, ecology, agriculture, and earth sciences. They share a concern for the material impacts of computation and aim to cultivate computing practices that support the well-being of both humans and other species within ecological limits (Nardi et al. 87).

LIMITS organises yearly workshops where research into computing within climate- and climate justice-related limits is presented and discussed, infusing ecological thought into the computing research agenda. Rather than focusing solely on the direct material limitations of our environment, they adopt broad understanding of limits, which they define as "limits of extractive logics, limits to a biosphere's ability to recover, limits to our knowledge, or limits to technological 'solutions'" ("Limits 2024"). This perspective aligns with the premise of digital post-growth, addressed in the 2024 LIMITS workshop, where Girard et al. presented research laying out the field-word required for digital de-escalation.

They argue that as technology becomes ingrained in society, it becomes difficult to reduce our reliance on it (Girard et al. 7-8).[14] In proposing strategies to overcome these barriers, Girard et al. highlight the role of bottom-up, self-organised approaches to localised problems in reducing reliance on overly-complex structures (1). A shift from

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[13] Anna Tsing re-tells the legend, told in China and Japan, that when Hiroshima was destroyed by the atomic bomb in 1945, the first living thing to emerge from the blasted landscape was a matsutake mushroom (3).

[14] Their thesis builds on the argument that large-scale digital technologies contribute to infrastructural and socio-political complexities, hindering digital de-escalation by making it harder to scale back or simplify our reliance on them. The complexity of these digital systems creates what they call "ratchet effects," meaning once a technology becomes ingrained, it becomes difficult to reverse or reduce its impact (Girard et al. 7-8). Modern societies carry the legacy of their industrial history, such as waste, overbuilt infrastructure and dependence on technology, which complicates transitions, both socially and materially.

global, top-down digital systems to localised, community-driven technologies allows for a *cosmolocalist* design and development process where knowledge is shared, yet production is decentralised and adapted to local needs. Cosmolocalism is the practice of global networking between locality-oriented initiatives, which become nodes in a variety of networks of place-based communities who share ideas globally (Manzini 76; Kossof 52). This model allows communities to share knowledge and resources globally while producing situated technical projects locally, reducing the reliance on global supply chains whilst contributing to the global digital commons (Girard et al. 8-9).

A complementary framework that builds on these principles is frugal innovation, which Tomlinson describes as a response to the sustainability challenge – namely in a future scenario of slow or negative growth – within the information and communications technology sector. Frugal innovation arises from research which takes place locally, in small-scale DIY centres and workshops, reusing existing tools to provide, often in an improvised way, homegrown and low-cost interventions for local problems. Favouring repurposing of old tools over pure invention, frugal innovation emphasises the diversity of practices, and ways of knowing which inform them, taking place away from well-funded, centralised research hubs (Tomlinson 26).

FarmHack and Open Source Ecology (OSE) are two platforms that harness the power of frugal innovation to move towards collective resilience. Both initiatives focus on empowering local communities to solve practical problems through the collaborative development of open-source tools. FarmHack brings together farmers, engineers and designers to openly create affordable tools for sustainable agriculture, independently from industrial suppliers (“Welcome to Farm Hack”). Similarly, OSE develops and catalogs open-source, low-cost, modular tools that enable small communities to build and maintain their own essential infrastructure with locally available materials (“About Open Source Ecology”).

These projects share a commitment to decentralisation, simplicity and adaptability, prioritising practical, low-complexity solutions over proprietary and energy-intensive alternatives. By encouraging reuse, localised production and global knowledge-sharing, they reduce reliance on global supply chains that are both costly and environmentally damaging. This approach not only mirrors the adaptive resilience of fungi in damaged ecosystems but also serves as a foundation for collective autonomy: a shift toward empowering communities to take greater control over their technical needs and their means of production. This shift provides a hopeful counter-narrative to the centralised, profit-seeking technological development championed by the dominant technology corporations, reminding us that “alternatives are possible and already exist” (Girard et al. 9).

<u>3c. Collective Autonomy</u>

Collective autonomy within the scope of this thesis refers to the ability for both human and more-than-human communities to have agency over their technical needs. More specifically, having significant influence over the thinking that informs the technological tools they rely on, the conditions they are developed under and therefore the values that are infused in, and the narratives that arise from such tools.

At the foundation of any possible change, small or big, to the ways we build technology, lies agency. Centralised, top-down and often opaque systems, such as the vast majority of the software we rely on, massively reduce the agency of anyone outside the small elite that operates and owns these systems (Bridle, “An Ecological Technology”). As we have seen, decentralisation by means of open-source architectures, co-creation processes with non-technical stakeholders and situated technological projects with global reach all enhance collective autonomy over digital tools.

However, in aligning these initiatives with a strategy for survival of the commons, it is important that we extend our focus beyond their design and development and identify ways to provide long-term structural support so that collaborative and situated software projects can continue to serve, not only the issues they tackle, but the broader global communities that might also benefit from them.

Radical Data explain the work they have done on *Queering the Map*, a community-generated mapping interface to record queer experiences related to physical places. This project was originally developed by Lucas LaRochelle as a class project in 2017, and it gained a lot of popularity shortly after (“Queering the Map”). With this attention came requests from other marginalised communities around the world who wanted to build their own collaborative maps documenting their experiences. Yet software takes time, resources and technical skills to maintain. Much code arising from digital activism, RD explain, is developed in isolation, in conditions where time and skills are scarce, and is sometimes closed-source, making it hard for others to understand and adapt.

RD open-sourced *Queering the Map* and improved its performance, allowing it to support the tens of thousands of entries it now has. Beyond just upscaling it to better support its direct community of users, they also modularised it, making it easier for people to adapt it, to build their own community map.

Modularisation refers to the practice of dividing the functionality of a program into smaller, independent, and reusable components or "modules." Each module contains the necessary code to execute one aspect of the whole program, which can be developed and iterated on independently without affecting the entire system (Narduzzo and Rossi 86, 89-90). Modularisation, according to RD, makes sense at a tactical level, making a project easier to build and maintain by basing it on existing open-source infrastructure, and at a political level, by rendering local digital activist projects generalisable to a global audience that might benefit from similar software.[15]

Queering the Map underscores the challenges and opportunities in fostering collective autonomy through digital projects. While self-initiated, activist and contextually situated software can empower communities to address their specific needs, such initiatives do not fall into a cosmolocalist model by default. For localised projects to move beyond their immediate contexts and contribute meaningfully to the global commons, they require technical and financial support structures that ensure their long-term sustainability, allowing them to remain adaptable and impactful.

By open-sourcing and modularising *Queering the Map*, RD not only enhanced its functionality but also empowered other communities to leverage and localise the tool for their own needs. This approach exemplifies how collective autonomy can be scaled and sustained, enabling technology to serve as a liberatory force that amplifies diverse experiences and versions of the truth while reducing reliance on centralised systems.

To create resilient systems that align with ecological limits, we must also reconsider the scale and complexity of technological designs. The approaches seen so far aim to scale up projects, increasing capacity and reach, but scaling down – radically simplifying technology – offers an alternative and equally vital pathway to autonomy. By designing for minimal energy consumption, minimal dependencies and adaptability to local contexts, low-complexity and low-bandwidth software provides ways to navigate the challenges of limited support structures and precarious environments.

CollapseOS is an operating system designed “in the abundant present for use in a future of scarcity” (“Collapse Computing”). It exemplifies this minimal approach by embracing radical simplicity to address a pressing question: how can communities preserve essential technical skills and tools in the absence of essential infrastructure?[16]

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[15] RD gives the example of facial recognition software developed for identifying the perpetrators of police violence against protesters. Although activist communities in different countries can benefit from this technology, some countries consider their development illegal. Thanks to techniques such as modularisation and open-source code, activists in places such as the Netherlands can legally and openly develop such tools and make them globally available, decreasing the risk of persecution of developers elsewhere.

[16] Such an event could be seen as a speculative civilisational collapse, though it becomes more immediately relevant if we consider temporary collapses in the wake of natural disasters or war.

This operating system is designed to be as self-contained as possible, running on minimal, scavenged and improvised hardware. Its goal is to enable users to build, program and maintain critical technological systems even under the most precarious conditions ("Collapse OS"). By prioritising self-sufficiency and modularity, *CollapseOS* shifts the focus from computational complexity to resilience and autonomy. It illustrates how scaling down complexity can help communities reclaim agency over their technical needs, fostering systems that endure and adapt within the most extreme ecological and material limits.

Similarly, the *Windternet* project reimagines server practices working within the constraints of renewable energy sources like wind and solar. Unlike traditional server practices that rely on energy-intensive cloud computing, *Windternet* proposes a firm commitment to material limits, laying out speculative, ecologically regenerative approaches to server technology. This includes creating compostable wind turbine blades from mycelium, repurposing electronic waste for power generation and designing open-source charge controllers for low-power, community-owned servers (Snodgrass et al. 1). By integrating principles of regenerative agriculture into technological design, *Windternet* challenges extractive practices and offers a model for community-driven, ecologically-centred computation. It demonstrates that centering ecological commitments can lead to technologies that still serve immediate community needs but also contribute to repairing damaged socio-ecological relationships.

Low-Tech Magazine's solar-powered website offers a present-day working example of how a server that firmly respects the constraints of renewable energy can function. Being fully solar-powered, the server, self-hosted in Barcelona, experiences regular down-time, depending on the weather to remain accessible online. However, the choice of designing their website to radically reduce the energy use associated with accessing their content aligns with *Low-Tech Magazine*'s mission to question new technologies in favour of more sustainable energy practices ("About the Solar Powered Website"). Their example illustrates that practicing technology more sustainably, while challenging, is ultimately a choice – one that reflects clear commitments to ecological values. Other organisations, projects and individuals with similar dedication have the agency to make such decisions, even if it means accepting limitations on conventional computational performance.

Lastly, building technology for collective autonomy comes with a responsibility to understand and question the intentions behind our desire for agency within technological and environmental systems. It is vital that we differentiate agency as a form of empowered participation from domination and control as a means of asserting human superiority.

This thesis opposes and tries to move beyond a lack of agency that is rooted in the design of centralised technological systems which are imposed and operate on extractive and domineering logics, leaving individuals feeling powerless to challenge them. Despite advocating for collective agency for both humans and more-than-humans, Bridle ("An Ecological Technology") argues for giving up control as a rejection of the human impulse to dominate, which leads to exploitation and harm. They are not rejecting agency itself but challenging the harmful assumption that agency means absolute control.

Instead of trying to master systems through control, they propose a collective, relational and responsive form of agency – one that listens, adapts and collaborates with the "more-than-human chorus." Such agency requires embracing our embeddedness in systems we cannot fully control or completely understand. Bridle draws on the idea of unknowing as a way to move beyond the limitations of human-centric perspectives and ways of "knowing the world" that are deeply rooted in colonialist and imperialist logics. By admitting that we cannot know everything and we cannot control everything, we step away from domination and towards coexistence (Bridle, "An Ecological Technology"). This shift allows us to approach complexity with humility, opening up space for more ethical, participatory and reciprocal engagements with the technological and living systems around us.

Conclusion

The growing body of work contributing to an ecological and equitable turn in technology is an important effort represented by both academic and activistic initiatives such as Permacomputing, LIMITS, Radical Data and many others. These initiatives often reflect a bottom-up, self-organised ethos that has significantly enriched the diversity of practices within technological development. While this thesis engages with specific case studies and methodologies, it situates itself within this larger ecosystem of thought and practice, contributing to the ongoing reimagining of technology. Central to this reimagination is the need to challenge anthropocentric values embedded in contemporary technological paradigms and extend methodologies that prioritise inclusive collaboration. In this thesis, I argue that the deeply relational forms of intelligence exhibited by fungal networks provide a powerful lens for addressing both these challenges and reimagining our approach to technology and ecological coexistence.

As pointed out in Part I, anthropocentric values embedded in the technology industry, stemming from a historical and ontological detachment of humanity from the living world, play a significant role in driving the climate crisis. Technology strongly influences public opinion and the ways in which humans relate to the broader living world. Modern technologies such as artificial intelligence, shaped by corporate interests, perpetuate an anthropocentric worldview that normalises ecological degradation in the name of profit, and a limited conception of intelligence as exclusively human.

Fungi, on the other hand, as demonstrated by their ecological significance and relevance to the humanities, offer a compelling living, ecological model for systemic thinking. Their role as ecological interfaces centres relational networks and interdependence as crucial principles for re-thinking coexistence in both ecological and technological systems. Challenging individualistic and control-oriented frameworks, fungal networks inspire a shift toward reciprocal, fluid and decentralised models, operating on principles such as mutualism and distributed agency.

Open-source software and its communities exemplify these principles but must go further, actively incorporating diverse social, cultural and ecological perspectives by addressing the needs of non-technical and ecological stakeholders. Participatory design methodologies, as demonstrated in Radical Data's workshops, offer practical strategies to extend agency and foster inclusive collaboration in technology. These efforts mark an essential foundational step toward more equitable software, rightfully valuing non-codified knowledge systems as crucial to re-thinking technology. Building on this groundwork, the next step requires incorporating more-than-human perspectives into design processes, granting greater agency to ecological systems, non-human entities and multi-species communities.

Such a goal must resist growth-centric and solutionist tendencies, which reduce complex eco-social issues to narrowly defined, temporary fixes such as carbon capture and storage. These perpetuate exploitative practices of environmental degradation and corporate greenwashing and divert resources from equitable, community-driven approaches. Drawing from fungi's keenness to form symbiotic relationships with other living species, a survival strategy that prioritises whole ecosystem health, this thesis proposes new metaphors for decentralised and ecologically aware collaboration in software development rooted in a strategy for survival of the commons – the shared systems that sustain life on Earth.

This strategy is built on three core principles: **Contextual awareness** (1), a fungal principle which can be mirrored by reframing dependency mapping as a practice of ecological and social inquiry, grounding software development in its broader material contexts; A **conservative understanding of limits** (2) – both the limits to perpetual growth and to the Earth's capacity to sustain and recover from the material consumption driven by this paradigm. This perspective is reflected in the work of the LIMITS research community and in frameworks such as cosmolocalism and frugal innovation; **Collective autonomy** (3) over technological tools and the values that inform them. While bottom-up, open-source software already fosters greater agency over technological tools, this can be further supported through strategies such as modularisation, designing for radical simplicity and adaptability, and prioritising ecological commitments in software development, even when these introduce challenges to functionality.

Looking ahead, this research invites further exploration into the challenges and possibilities of integrating more-than-human forms of intelligence into technology design. It must contend with several challenges: resistance to structural, post-growth change; the deep-seated attachment to centralised, top-down technological systems; and the difficulty of representing the rights and agency of more-than-human beings and systems in both technology and its development processes. Despite these hurdles, embodying fungal models of collaboration and resilience fosters a relational and interdependent understanding of the living, ecological and technological systems we are an inseparable part of. It can inspire and guide frameworks and technical tools that not only address the challenges mentioned above but also nurture decentralised, ecologically-centred and equitable approaches to technology. This does not require inventing entirely new methodologies but rather building on the diversity of existing practices of making technology otherwise, rooted in collaboration and ecological awareness. Change is not only possible but already underway, as these efforts demonstrate, reminding us that we are not without agency.

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