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MATERIAL-LED RESEARCH: A POSTHUMANIST METHODOLOGY FOR MAKER EDUCATION PRACTITIONERS

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Abstract: *This article explores material-led research as a posthumanist methodology for practitioner-researchers in the learning sciences to study their own making practices, methods, and outputs. Unlike other first-person methodologies, material-led research aims to challenge and decenter the practitioner's perspective through curious attention to the role of materials in their practice. Using the case of the first author's engagement in biomaking—where living materials mingle with other ones—we illustrate a method for following the materials by attending to material assemblages, noticing what materials do, and reading them longitudinally. We discuss how, by granting materials an active participation in making practices, we allow ourselves to appreciate how they disrupt, influence, and offer new possibilities for making and learning.*

Keywords*: posthumanist methodology; post-qualitative inquiry; practice-led research; new materialism; environmental education; maker education; biomaking; biodesign.*

Introduction: Grounding our making practices

Together with other fellow creatures, we have shaped the crust of the earth; while we gather mud and minerals to build our houses, ants carve tunnels, trees make atmosphere, beavers shift the course of rivers, and so on. For us humans, there is something deeply gratifying about *making* something out of materials. As educators and researchers who build and study learning environments that engage others in making, we think a lot about how we can support students to build things and solve problems—we give them materials and tools and celebrate their wondrous crafty creations. Furthermore, we are proud makers ourselves and enjoy trying new technologies as much as making new ones. Yet, the sense of accomplishment carried with making is sometimes silently coupled with a flawed sense of mastery and power over the material world.

This article wrestles with our personal experience of making in a posthuman world, where our delusions of control over our tools, technologies, materials, and nature are continually contradicted by social and planetary unraveling. The discourse of the "Anthropocene" acknowledges how modern human practices have altered the functioning of the planet (Crutzen & Stoermer, 2000). We argue that one way of rethinking maker education in the Anthropocene is by paying further

attention to the material tensions and flows created in making by human and nonhuman actors. Instead of seeing making as a way of shaping the world to our own will, we can think of making as a practice of learning to live in productive partnership with other material forces of the earth and a movement towards much-needed reconciliation, reparation, and regeneration of the living world.

As an educational practice, making is about allowing learners to engage with materials and technologies to build personally meaningful and shareable ideas (Halverson & Sheridan, 2014). Makerspaces (Peppler et al., 2016) are places of active material gathering where students experience the elasticities, textures, and resistances that different materials afford. Material exploration is particularly salient in the small basement lab where this study occurred. In this place, some raw, wet, breathing, living materials—such as mycelium fungi, bacterial cellulose, and slime mold—mingle with other more dry and cold materials and technologies.

The line between living and non-living materials gets blurry when the practices of making and growing blend together (Bunn, 2014; Field, 2016; Ingold & Hallam, 2014). Most materials commonly encountered in educational makerspaces—such as wood, acrylic, metal, and textiles—seem stable and passive but they are in a constant, though often slow, state of change. Living materials, on the other hand, seem to move and pulsate at a faster pace. Here, we define living materials as those which flow through autonomous and self-regulated bodily structures that are metabolically alive (Boden, 1999; Weber & Varela, 2002). Though living materials exist in continuity with the rest of matter that flows on the living earth, we see value in distinguishing them to identify and describe the movements that different materials bring into multimattered and multispecies making practices.

One such multimattered and multispecies making practice is biomaking. Biomaking, or making with biology, involves the integration of living organisms into the design process to create bio-based materials for practical or conceptual applications in areas including health, food production, fashion, construction, and manufacturing (Kafai et al., 2020; Lui et al., 2019; Tocchetti, 2012). Biomaking is not new. Several of its practices stem from indigenous knowledge and design methods (Blanchette et al., 2021; Pettigrew et al., 2010; Watson et al., 2021), while others can be traced back to home cultural practices of cooking and crafting (Jen, 2015). Recent developments in biotechnology have made possible new forms of engaging with biology in ways that center creative material production, much like other maker activities (Walker et al., 2022). These advancements and increased availability of low-cost resources have propelled the growth of educational initiatives around biomaking. There is an emerging body of work concerned with understanding the continuities and discontinuities between making and biomaking (Kafai et al., 2020; Lui et al., 2019; Walker & Kafai, 2021), between tools for digital and biological fabrication (Zhou et al., 2022), and also between makerspaces and community laboratories for creative engagement with biology (Walker et al., 2022).

As we move towards increasingly hybrid worlds, Haraway (1997; 2016) argues for new methods and frameworks to be capable of thinking with technoscientific practices that unravel the boundaries between the human and the nonhuman. Emerging digital technologies such as artificial intelligence and machine learning stand side-by-side with innovations in biotechnologies such as gene editing, biosensing, and biofabrication, opening up new frontiers in human and nonhuman

collaboration. Biomaking, like all technological movements, is not neutral (Strate, 2012). The proliferation of its practices can either reinforce narratives of domination and subjugation of the living world and appropriation of indigenous knowledge (Ginsberg et al., 2019) or can open our imagination to new, and in some ways ancient, forms of interspecies cohabitation that present day' science and technology are revindicating.

Mi'kmaw elder Albert Marshall (Bartlett et al., 2012) speaks of "Two-Eyed Seeing" as a guiding principle of "learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of Western knowledges and ways of knowing … and learning to use both these eyes together, for the benefit of all" (p. 1). This critical yet embracing perspective guides us in navigating hybrid ancient-future technologies such as biomaking. On one side, we look through cognitive theories informing the learning and life sciences. On the other side, through posthumanist theories grounded on ontologies and epistemologies that share fundamental features with indigenous worldviews (Bignall & Rigney, 2019; Todd, 2016; Watts, 2013). However, we, the authors, do not belong to indigenous communities and at most, consider ourselves modest apprentices of their ways of being and knowing. While we do not feel prepared to root this work on indigenous perspectives, we do acknowledge the intersectionality of this inquiry and recognize indigenous intellectual authority and wisdom in the ontologies and epistemologies that guide this methodology.

Looking through the intersection and tensions between different ways of knowing, the material-led research we propose in this article aims to serve practitioners—makers, educators, and researchers—in studying their own maker practices to guide ecologically mindful pedagogies for making in the Anthropocene. The expectation is that, by attending to the subversive quality of materials in making, we may find better ways to get along with them as educators and gain awareness of the ecological implications of our practice. We wonder, for example, how might our design decisions as educators and facilitators change when we have a deeper understanding of what materials do and what they don't, where they come from and where they go, and what traces we leave on each other. Looking into the first author's biomaking practices, we ask how material-led research can foreground for the practitioner (1) knowledge and awareness about the active participation of nonhuman entities in making and (2) the ethical and environmental implications of making practices.

To answer these questions, we begin by describing practice-led research as a foundational methodology from which material-led research stems as a posthumanist alternative. We then lay down the theoretical grounds of the methodology by referencing new materialist philosophies and their application in the learning sciences. Building on that, we describe three methodological moves suggested for practitioners to be able to follow their materials and gain knowledge on environmental ethics. Moving into the study design, we describe the settings and context of the biomaking case study used to implement the methodology. Then, we put material-led research to work through a series of stories and products that emerged in the process of following the materials. These stories and products are leveraged in the discussion to highlight how material-led research can be relevant for the study and design of broader educational making practices with an increased awareness of material implications.

Methodological background: From making from the inside to making from within

As a response to the challenges of studying knowledge that is immersed in the body and situated, a growing number of scholars, especially in craft, arts, and design research, are adopting self-ethnographies—such as sensory ethnographies and practice-led research—to gain insight into their own creative practice (Candy, 2006; Groth & Makela, 2016; Mäkelä et al., 2011; Nimkulrat, 2012; Pink, 2015; Pinnegar & Hamilton, 2009). For example, weavers who study weaving, programmers who study coding, gardeners who study gardening, and so on. Practice-led research is grounded on two interrelated ideas. First, that making *is* a method of understanding and sharing knowledge and, therefore, creative work is in itself a research practice (Smith & Dean, 2009). In the words of Heimer (2016), "[w]hen artists and designers research through making, the product as artefact and the process are not only data, but also part of the articulation" (p. 03). And second, that the highly specialized knowledge of practitioners can lead to valuable scientific insight for the understanding of creative practices (Smith & Dean, 2009).

Whereas practice-led research has gained momentum as a legitimate scientific practice in the arts and crafts, this article explores its potential for studying learning that happens through making in educational research. In the learning sciences, it is common to use design-based research to iteratively build technologies for students in order to understand learning (Edelson, 2002; Wang & Hannafin, 2005). Yet, for the most part, research focuses on the implementation of technologies and not on the making of them. The study of those making practices by learning scientists themselves (as practitioner-researchers) can be of significant value to our understanding of learning and for the creative development of the tools, technologies, and experiences we create. As research on constructionism has shown (Lin et al., 2020; Papavlasopoulou et al., 2017; Valente & Blikstein, 2019), through making, we learn to learn, we become apprentices of our materials, we know in our bodies what they *do* (and what they don't). Similarly, anthropologists have observed how intimate and persistent engagement with materials can sharpen practitioners' observational skills to subtle visual and tactile clues that materials offer (Ingold, 2013; Malafouris, 2008). This tacit knowledge (Collins, 2005) certainly informs our design choices. Still, it is admittedly challenging to articulate—discursively or otherwise—and, perhaps because of the lack of methodologies and publication venues, it is rarely documented and shared.

One of the main advantages of practice-led methodologies is the high degree of precision when articulating bodily engagement with materials. By thinking *through* making rather than *about* it, practice-led studies tend to result in nuanced accounts of subtle perceptions of the body when interacting with materials (see Heimer, 2016; O'Connor, 2007). On the other hand, one of the potential flaws of centering solely on the first-person experience is that it is easy to dismiss or ignore how practitioners not only affect materials but are also affected back by them. In other words, it is hard to shake away our deeply ingrained delusion of control and immerse ourselves in the materials at work, especially when focusing so heavily on our own actions and perceptions. Ultimately, the challenge of self-study is about freeing oneself of what one already knows and remaining open to the unexpected.

As a first-person methodology, material-led research aims to capture making practices from an insider point of view while simultaneously decentering and challenging the practitioner's perspective by following multiple material forces affecting their practice. Deleuze and Guattari

(2004) observe that materials are not fixed or homogeneous but "in movement, in flux, in variation," and thus, "this matter-flow can only be followed" (pp. 451-52). In the next section, we explore how following the materials may help practitioners situate their work within a humming and vibrant material world.

Theoretical grounds: Dissolving objects into materials

Central to posthumanism is a critique of the objectivity of the world or its conception as a collection of bounded and self-contained objects to be defined, classified, and categorized (Alaimo, 2014). Without a doubt, it is through a systematic depiction of objects of study that science has so effectively advanced our understanding of the universe. Yet, this perspective is less suited to understanding reality as the entangled phenomenon that it is, which is fundamental to appreciating the ethical and ecological reverberation of our actions as part of it (Barad, 2007). To that end, posthumanist thinkers from different disciplinary realms offer a perspective of the world not as a sum of objects but as shifting amalgams of intertwined material bodies (Alaimo & Hekman, 2008; Barad, 2007), things (Bennett, 2010), or matter-flows (Deleuze and Guattari, 2004; Ingold, 2013).

Barad (2003) argues that materials, unlike objects, are not bounded, unitarian, and static entities. Neither are they "little bits of nature" passively waiting for human meaning-making (p. 821). Materials cannot be reduced to human semiotics and escape exclusively human contexts (Bennett, 2010). This posthumanist take on matter has several implications for the study of learning and making. Hultman and Lenz Taguchi's (2010) "relational materialism" brings together several feminist poststructural philosophies to foreground the material dimension of learning and the relational emergence of knowledge as a process of becoming. For example, in a study of the shifting spatial distribution of materials and technologies in a makerspace, Keune and Peppler (2019) note how material changes can inadvertently shape social positionalities and learning opportunities. It has also been documented how materials may draw people into learning and discovery (Pacini-Ketchabaw et al., 2016; Penfeld, 2019) or how they may actively resist human manipulation or invite other material bodies into dialogue (Sheridan et al., 2020).

Pacini-Ketchabaw and Boucher (2019) observe how materials in learning, such as clay, are unfolding historicity for being loaded with knowledge, meaning, and power. The authors note how, before clay gets into children's hands, it travels through geological times, undergoes violent extraction from occupied indigenous lands, and is made placeless when inserted into systems of capital exchange. Posthumanist exercises of longitudinal and material mapping (see also Bennett, 2010; Genosko, 2018; Tsing, 2015) center often unpredictable and sometimes unwanted reverberations of the encounters between human and nonhuman bodies (Alaimo, 2010). Seeing through materials also enables a conception of "thinking as the stuff of the world" (Alaimo, 2014). For example, clay is not just a passive object eliciting children's knowledge but also a knowledge in itself; it is compressed, earthy, and evocative knowledge about weather and geological events, bustling microorganisms, and human concerns. "Claying," as Pacini-Ketchabaw and Boucher (2019) call the art of caring for earth's caring relations, is an old exercise of thinking *with* the land. In practice, attending to materials through their temporally and spatially distributed stories can leverage knowledge about their relational activity with human and nonhuman actors and provoke questions about their ethical and environmental implications.

Methodological framework: Delineating material-led research

> "The difference between a marble statue and a rock formation such as a stalagmite, for example, is not that one has been made and the other not. The difference is only this: that at some point in the formative history of this lump of marble, first a quarryman appeared on the scene who, with much force and with the assistance of hammers and wedges, wrested it from the bedrock, after which a sculptor set to work with a chisel in order, as he might put it, to release the form from the stone. But as every chip of the chisel contributes to the emergent form of the statue, so every drop of supersaturated solution from the roof of the cave contributes to the form of the stalagmite. When subsequently, the statue is worn down by rain, the form-generating process continues, but now without further human intervention" (Ingold, 2013, pp. 21-22).

As illustrated by Ingold's quote above, following material transformations without strict distinctions between human and nonhuman actors reveals a broad and egalitarian perspective of the making activities and morphogenetic processes that configure the world. A closer look at the narrative reveals three moves—attending to material assemblages, noticing what materials *do*, and reading them longitudinally—used to capture material flows and foreground multispecies and multimattered participation in making practices. We leverage these methodological movements to guide practitioners in studying their making practices through material-led research.

Attending to material assemblages

The forms of the statue and the stalagmite emerge from productive and relational encounters between material bodies. First, Ingold draws our attention to the meeting between bedrock, hammers, wedges, and quarrymen. The focus then shifts to the hands, chisel, rock, and chips, and finally to the interaction between rain and statue. Ingold (2011) uses the term "meshwork," and Deleuze & Guattari (2004) coined the term "assemblages" to refer to these unfolding and loose entanglements involving human and nonhuman entities in specific times and places (Nordstrom, 2015). In both concepts, entities are not represented as bounded objects connected by lines of relationships (as in actor-network theory or activity theory) but as lines in themselves (Deleuze & Guattari, 2004; Ingold, 2011). Assemblages such as hands-chisel-rock-chips are entanglements of material flows or lines by which things continuously become with one another. Therefore, forms in the world—such as a stalagmite deposit, a stone statue, a gastropod shell, or a 3D printed model—emerge from shifting assemblages made of intertwined material bodies that cannot be followed in isolation but only in relation to each other.

Noticing what materials do

In following materials flows, Ingold describes how "every chip of the chisel contributes to the emergent form of the statue" and "every drop of supersaturated solution from the roof of the cave contributes to the form of the stalagmite." Practitioners and makers know that materials can be better understood not by what they *are* but by what they *do* (Ingold, 2013). For example, stone carvers know that when in touch with the chisel, alabaster *flakes* and *splits* along hidden cracks, while marble's fine grain *holds* itself together, allowing for minute details. Importantly, materials do

things even in the absence of human action, just like the statue wears down under the rain. For example, makers in digital fabrication know that plywood *bend* if stored horizontally given ongoing enmeshment with environmental moisture (for air is a material substance as well), which pulls its different fibers unevenly. Materials can be followed through keen sensory attention to what material bodies are doing moment to moment as they unfold within material flows.

Reading materials longitudinally

Every drop of rain contributes to the ongoing sculpting of the statue, just as every chip of the chisel did before. Ingold's (2013) reading of making and morphogenesis is not from a lateral but a longitudinal and forward perspective, which discloses how forms arise incrementally over time through ongoing material engagement. To discern this process, the attention focuses on the traces that bodies leave upon each other (Deleuze & Guattari, 2004). For instance, when looking into a tree's annual rings, a longitudinal perspective reveals not simply a static snapshot of past climate but a dynamic story of ongoing relationships and material flows between cells and surrounding molecules. Slow material interchange during dry summers leads to denser cells and darker rings, whereas larger cells and lighter rings of fast material interchange and growth are characteristic of springs. Similarly, a 3D printed model can be read as a story of engagement between the PLA filament, heat, a moving extruder, and a solid base. If the extruder gets stuck along its axes, the resulting shape will certainly reveal it. Forms are never definitive or finished but only a more or less stable occasion in the flows of substances and material circulations. In the words of Barad (2003), material bodies are "always already an ongoing historicity" (p. 821).

These three methodological movements—attending to material assemblages, noticing what materials do, and reading them longitudinally—provide a path for practitioners to follow the materials in their work. More than a recipe that must be applied in a specific order, these strategies are meant to iteratively open paths or questions that stimulate new lines of material-intellectual inquiry.

Building on practice-led research, the study occurs, for the most part, during the practice itself (Heimer, 2016; Smith & Dean, 2009). In material-led research, making *is* the methodology, an iterative process of data and material gathering in response to unfolding questions. Unlike traditional qualitative methods, where data collection usually precedes data analysis, material-led research temporally collapses these activities. From the entangled material-intellectual activity of making, knowledge—being in the form of artifacts or words—sprouts. This approach is informed by emergent post-qualitative approaches in their search to produce knowledge beyond descriptive representational language (MacLure, 2013; St. Pierre, 2018). Barad (2007) says that "knowing is a matter of part of the world making itself intelligible to another part of the world" (p. 185) and that can take many forms.

Material-led research revolves around the knowledge that materials hold and the questions they provoke. This material inquiry is akin to Semenec's (2021) "unruly encounters," unremarkable but puzzling events that, despite their banality, command attention precisely because they refuse explanation. Similarly, MacLure (2013) refers to "data that glows" to describe events that demand but refuse interpretation. Rather than trying to extract explanations or patterns to 'capture' what is unraveling, glowing data demands to follow the momentum of the event that "caught us up in

order to arrive somewhere else" (p. 662).

Material-led research differs from practice-led research in being a diffractive (Barad, 2007; Haraway, 1997) rather than reflective methodology. Whereas most self-studies recursively reflect *back* into the practice to provide a clean and mirrored depiction of processes (Mäkelä et al., 2011), material-led research diffracts *forward* through material and intellectual production. Given the inextricable relation between knowing and being (Barad, 2007), researchers cannot move into a "third party" neutral position to reflect and provide a distanced picture of their own seeing and thinking (Hultman & Lenz Taguchi, 2010). Research is, instead, an instantiation of ongoing knowledge production that carries forward what was once experienced through unfolding material-intellectual assemblages.

In terms of analysis, the non-linear and diffractive methodological approach can result in some peculiarly fuzzy boundaries between what we traditionally call data and other pieces of knowledge that emerge during and after practice. Taylor (2013) applies Levi-Strauss' concept of the bricoleur in research to describe this process. She describes the researcher as a curious and creative being "who gathers or collects all manner of ideas, things or elements that 'might … come in handy', and who then selectively pieces these assorted collected entities together to create an inventive assemblage or bricolage" (p. 63).

Material-led research aims to extend current posthumanist methodologies by exploring what it means to diffract not only theoretically but also materially. Thinking diffractively is for Haraway (1997) about making "a difference in the world" by attending to "the interference patterns on the recording fields of our lives and bodies" (p. 16). Making a difference in one's practice is central to material-led research as a practice where thinking and doing cannot be separated and, through which, material-intellectual products emerge.

Study context and methods: setting up for making

While working on the design of pedagogical materials and frameworks for biomaking, I, the first author, engaged with fungi for three months, three times a week, for at least three hours a day. The development of material-led research emerged from the need to document the performance of living and non-living materials, which had the unexpected effect of balancing the overwhelming weight and certainty of the maker's perspective.

Participants were—in any order and among other material bodies—gloves, water, wood chips, plastic containers and bags, mycelium, and me. I chose mycelium as a partner organism, moved by a growing curiosity about the fungal kingdom. This interest emerged during the COVID-19 pandemic. While attempting to make sense of decay in human and natural realms, I casually came across a mushroom at an urban park. Although mushrooms are often associated with decomposition and death, I learned that they also sign new beginnings. I realized that mushrooms were the only visible part—or fruiting body—of a much larger organism known as mycelium (McCoy, 2016). Mycelium is a multicellular structure of threadlike tissues that lives underground, growing through decaying wood or leaves and within plant roots, and it plays a crucial role in interconnecting, nourishing, and regenerating forest ecologies (Stamets, 2005). Mycelium grows by expanding outwards from its hyphal buds, the tip of each of its threads which are constantly searching and digesting water and nutrients (Moore, 2005). This organism can be cultivated

relatively easily by inoculating a carbon-rich substrate (such as wood chips, grains, or even disposable paper cups) and providing certain temperature and humidity conditions. In biomaking, building with mycelium consists of leveraging the organism's capacity to act as a living glue. The inoculated substrate is poured inside a mold so that this meshy organism can fuse all pieces of matter until the structure holds together on its own and can be unmolded. Some of the advantages of mycelium as a living material for education is its ubiquity and accessibility (given its vital role in most ecosystems), its ability to grow in relatively short periods of time and with enough reliability, and its malleability to shape a vast and largely unexplored array of forms and materials (Correa & Holbert, 2021).

The study took place in a small making lab in the basement of a university campus. The lab was equipped with tools for digital fabrication (laser cut, electronics, craft materials, etc.) and essential biomaking tools and ingredients (flow hood, pressure cooker, growing chamber, agar plates, scalpels, organic substrates, etc.). The space was supplied with data collection instruments such as an infra-red video camera above the main working table, a time-lapse camera over a growing chamber, and audio recorders to register thinking out loud while making. I also carried a journal with notes and drawings of my process and a phone to take pictures.

Unruly events were identified during the making practice—with a quick photo or journal note—or later while revisiting the data unfolding from construction. Some of these events elicited further critical diffraction, which was done by following the materials through engagement with new pieces of data, further making, and recursive writing. For example, when encountering a disruptive material, I would read it longitudinally by researching where it comes from, often leading to new creative explorations. Unruly events worked as an anchor to drive further research and production in a bricolage and open-ended approach. I recursively collected and assembled pieces of data coming from the lab (audio and video recordings, time-lapse videos, photographs, artifacts, journal notes, gathered materials, and also persistent memories, olfactory recalls, and visual synapses) together with other knowledge fragments from outside of the lab (posthumanist theories, newly found materials, extracts from scientific books and media, fragments of videos about microscopic activity, and articles on mycology and paleontology). I used a digital board to visually spread these data fragments and arrange and rearrange them along with thoughts, feelings, emerging narratives, and new data streaming from the making process. Rather than thinking about all these pieces as distanced, discrete, stable, and defined representational categories, I tried to make sense of them by positioning my present self—the entire amalgam of thoughts, emotions, bodily feelings, surroundings, etc.—within the assemblages that emerged and diffract forward by following the creative leads that they offered through further making or writing.

Making as a diffractive methodology was undertaken materially, through physical engagement with matter, and verbally, through the craft of writing that speaks to the liveness of things themselves. Responding to MacLure's (2013) call to move beyond a pure representational logic and further engage with "the materiality of language itself" (p. 663), I attempted to convey the embodied utterances of my making experience as well as the speculated experience of my nonhuman counterparts. I drew from Abram (1988)'s notion of language as "the voice of the living Earth itself" (p. 118) and Blaise and Hamm' (2019) lively animate storying, which aims to challenge human exceptionalism through grammatical effects—such as using lively nouns and pronouns and shifting sentence structure—to blur distinctions between nature and culture and activate

multispecies worldings. As a result, stories and artifacts emerged by following and wrestling materially and poetically with the questions provoked by the materials themselves. In this process, the second author had a crucial role in following and challenging the tensions of posthumanist empirical research.

Ongoing results: Following gatherings between partners and other unexpected visitors

Story 1: Following Hyphal threads breathing at night

Delicate hyphal threads
dwelling silently in a muddle of wood,
industrial waste, decaying matter, dust in a bag.
For mycelium, an exquisite feast, a delightful treat.
Unfolding strings embrace every bit
of noble oak, beech, maple, and hickory.
Bifurcating, branching off,
making forward a thousand ways,
trading moving for growing,
becoming the traces of its own whereabouts.
Inside this humming breathing body,
fluid cosmos of nutrients and nuclei
swimming along a steady flow,
moving from and towards
the tips of this entangled maze,
where million hyphal buds
play an ongoing give-and-take.
Exuding crafted concoctions
enzymes expelled all around.
No hardwood is hard enough,
and shredded matter all becomes.
Carbon molecules easily join
the swifting currents inside,
Some leftovers are set aside
for other critters down the line.
Threads spread, breathe, sprout life, re-birth.
Hyphae and wood fold into one another
What is it like to become something else?
And just when there seemed to be no end,
a membrane strikes, a stubborn plastic halt
to this swiftly unfolding universe.

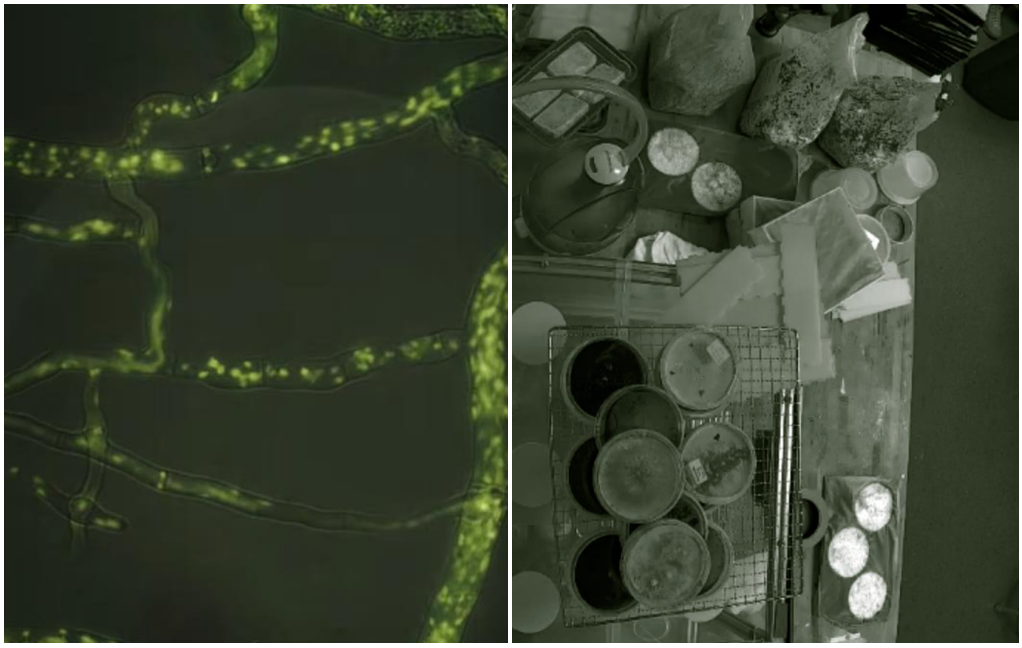

Fig. 1: Left: Mycelium moves nutrients and nuclei through fluid networks of cells (SciFri, 2014). Right: The working table at night under the infra-red camera.

All this happens while I am not there. For the most part, the forms I claim to make are made at night while I sleep, do emails, or brush my teeth. The first time I turned on the lab's live-stream camera from home, I quickly shut down the laptop. A feeling of being out of place crept up on me as if breaching an intimate room. The night after, I peered once again. Through the camera, it is dark and as quiet as it gets in the basement lab (Fig. 1). There is no movement except for the steady stream of steam coming out of the humidifier. In infrared duotones, I see the working table populated with ongoing breathing experiments—agar plates with mycelium samples, mushrooms collected from the local park, mason jars with liquid cultures, and three plastic bags. Each bag is filled with hardwood dust, pasteurized, and inoculated the day before with a local fungal strain and the "mother" mycelium of most of my experiments. The only visible sign of life is a dense condensation that builds up inside the plastic walls of each bag.

Story 2: Following vinyl and Ganoderma through ancient whereabouts

Six weeks after introducing mycelium into the wooden substrate, the previously loose content of the bag has turned into a single white solid mass. Each fragment of wood is wrapped by a delicate weblike tissue that connects one bit to the other, making a tightly knitted structure that takes the exact shape of the bag. Not a single folding or crease is left unexplored.

A dense cloud of isopropyl alcohol falls around the bag and over the table. Biomaking is as much making as it is cleaning, as much growing as it is killing. Contradictions abound. While fungi evolved in sympoietic relation with multiple other organisms, in the lab, it grows in carefully engineered sterile environments. Pasteurized substrates, distilled water, HEPA filters, lots of single-use plastics, and disposable syringes are routinely used to prevent mycelium from meeting any-body else. Practitioners also wear disposable PPA (personal protective apparel) such as surgical masks and vinyl gloves, not to protect themselves—these strains are innocuous to the human

body—but to protect the delicate and vulnerable body of lab-grown mycelium.

My hands in blue vinyl gloves enter the bag, and fingers begin to work with the newly formed mycelium-substrate structure (Fig. 2). The blue vinyl flickers against the raw quality of the substrate. Vinyl is a material wonder in the flows of becoming: Elastic but endurant, disposable but perennial, ancient and new. The rubbery material feels permanent, resigned to the seemingly perennial silhouette of a human hand that refuses to let go. Gloves are a constant reminder of the conflicts in my practice. A thin barrier that prevents my hands from meeting the organism that I call my partner. Rather than looking away, I follow the traces of these uncomfortably odd materials—through pieces of media and articles from paleontology and microbiology—to find out that vinyl and fungi had been mingling for quite some time.

Fig 2: Left: Hand in vinyl glove and mycelium growing in wood chips. Right: Artist's reconstruction of a forest during the Carboniferous period (Photo12/Ann Ronan Picture Library/Alamy, n.d).

Some 300 million years ago, and over a long period of time, carbon biomass stored in the skeletons of small marine organisms sank into the ocean floor. Over time, new layers of sediments and rocks buried the accumulations of their remains deeper and deeper, where the increased pressure and heat turned them into a thick layer of black and bright viscous liquid. This fluid dark matter rested underneath the earth's crust for time immemorial and until two-legged creatures started drilling the planet's crust for crude oil—millions of years of gradual material transformation released in seconds. Not long after, this slippery and greasy material was combined with chlorine, a compound found in regular salt, to make an incredibly malleable, versatile, cheap, persistent material: vinyl.

While following vinyl, I ran into an 1880's engraving by Robert Brown (Fig. 2). I showed fabulous ancient forests that also 300 million years ago covered the land during a period known as the Carboniferous. Trees in the illustration look different from the ones we know today; they had

branching fern-like spikes gracefully arranged on top of colossal 160 feet tall trunks made of cellulose and lignin—the same extremely tough fiber that allows trees to stay upright today (Krulwich, 2016). Despite their height, I learned that these trees had very shallow roots and fell over easily into the swampy waters of the forest floor (ibid). Yet, according to a prevalent paleontology theory (although not the only one, see Nelsen et al., 2016), no earthly critter could break down their tough lignin molecules (Floudas et al., 2012). Dead trees piled on top of each other, compressing under their own weight, deeper and deeper under increased pressure and heat, gradually building a layer of soft dark ignitable rock known as coal. Yet, data from geological strata reveal that quite sharply these trees ceased to accumulate, and a possible cause is the action of fungi (Robinson, 1990). After millions of evolutionary years, white-rot fungi became able to produce powerful enzymes capable of breaking down lignin and decomposing wood into smaller bits that form today's fertile soils and prevent the accumulation of organic matter on the earth's crust (Floudas et al., 2012).

Ganoderma Lucidum, the organism in the bag, is a white-rot fungus. Like its ancestors who long ago solved the riddle of lignin, it continues breaking down hardwood with ease. According to recent studies in mycoremediation, some of its close relatives have proven effective in breaking down other carbon-rich substrates like those derived from crude oil, including polyvinyl chloride, commonly referred to as vinyl (Akhtar & Mannan, 2020; Czaplicki et al., 2016).

Story 3: Following bodies in friction

I got a new box of disposable vinyl gloves: transparent ones as if my hands could see. When my gloved hand enters the bag, I take a moment to feel the nonhuman body I am about to meet (Fig. 3). The sense of touch is a keen one in this practice. Building a personal relationship with an organism that operates so differently is hard. Through odd sensory modalities, mycelium sees through without sight and navigates microscopic worlds that don't mean anything to me. But I do recognize something about my body in the fleshy skin of a mushroom. I know this organism mainly through touch, and I believe that is how it may also know something about me. Even through the plastic membrane of the glove, I note that my fingertips can still feel and assess the substrate's moisture by recruiting memories and sensations from my whole body. My gloved hand knows the humidity is right because it feels not coarse like sand but smooth and cold like the forest's floor after autumn rains. My hand is also reassured by the fresh smell of rotten wood that transports me instantly to a log bridge I used to cross as a child.

To cast mycelium into a mold, I first need to break down its newly formed network into very small pieces. Although it sounds counterintuitive, breaking mycelium down does not damage the organism but makes it stronger. In the words of Bierend (2021), "each fragment will carry on with their day, exploring around for food and mates, branching forward to reach new grounds, relinking whenever they meet another part of their larger former self." Mycelium evolved to be one and multiples at the same time. My hands submerge into the substrate, grabbing a chunk and sliding it through the fingers until its fibers come apart and disappear.

Fig 3: Left: Hands opening a bag of mycelium to break down the substrate. Right: Exposed nails after gloves ripped through ongoing friction with mycelium and wood chips.

There is a certain cadence to the acts of sensing, grabbing, sliding, sensing, grabbing, sliding, sensing, grabbing, sliding. I devote myself to these rhythms, sometimes for hours at a time. The ligaments of my finger, the lower back, and the soles of my feet start to complain. I am tearing down mycelium's body while mycelium tears down my body as well. Suddenly, my fingertips feel cold and wet: two fingernails poke out from the ripped gloves (Fig. 3). My skin and nails' microbiome are likely joining the party. Contamination concerns start to build up in my mind: I see myself in a week adding yet another bag of contaminated mycelium to the compost pile together with hours of work and growth lost. Without thinking twice, I throw the ripped gloves in the garbage. After 138 minutes of human use, millions of years of making are on their way to a landfill, where they will continue to mingle with other materials for more than 200 hundred years before being fully decomposed, not without leaving chemical traces behind. I put on new gloves, feeling overly aware of the bodies within my body and my futile attempts to restrain the multiples within myself.

Story 4: Following plastic-mycelium concoctions

The vibrant blue filament was hiding in the substrate (Fig. 4). Unmistakable synthetic and remarkably foreign to all the hemp chips around it. 'How did you end up here?' I wondered. The substrate in this bag is hurd, a by-product of the hemp industry that processes low-THC Cannabis sativa for industrial and medicinal use. Green fields of hemp are routinely cropped, dried, and pressed into bales. Industrial processing plants subsequently decorticate and sort hemp bales into different products such as long fibers, green microfiber, and hurd chips (Christensen, 2019). In the market economy, by-products are those unintended but inevitably produced when making something else. Like trash, sewage, or pollution, it would be easier for the market for hurd to go away. Nonetheless, hurd persists on the margins (Tsing, 2015), like a statement. In an attempt to

reinsert this stubborn material into capitalistic flows, hurd is sold as pet litter. Yet, hurd is as poor to humans as it is rich to life. Nutritious, antiseptic, and highly absorbable, hurd is an ideal place for mycelium's wayfinding and mushroom fruiting. The blue fiber that somehow snuck through industrial cropping, chopping, sorting, and sanitizing is also a by-product—an unintended but inevitable thread in today's hybrid techno-ecological matter flows.

Fig 4: Left: Blue plastic filament found inside of a hemp-mycelium culture. Center: Adding found plastic debris into mycelium. Right: Experiment with mycelium and plant-based bioplastic.

After this encounter, I start a diffractive and compulsive collection of plastic debris, tiny fragments, pellets, and filaments that persist, breaking off from their objects and joining streams of material flows (Fig. 4). I find them in dust cornered on the sidewalk, rainwater drainages, and playgrounds' sand. I carve for synthetic fossils that are all too common to be of any (monetary) value, marveling about their impossible colors and forgotten stories. Eventually, they make their way into my biomaking practice. Introducing them into mycelium shows their obstinate permanence and refusal to be reabsorbed by the biosphere while displaying the tensions between the circular and linear flows. Mycelium wraps its body around plastic fragments, forming a thin layer that results from hyphae moving on after not finding anything easy to break down. Later, I began exploring the entanglements of mycelium and plant-based bioplastics (Fig. 4). Carbon molecules are more readily available for the organism to digest in this less stable material, and slowly they fold into each other in a seamless material flow.

Discussion: unearthing knowledge and mindfully weaving earth tissues

Responding to our first research question, the stories show different ways in which encounters between humans and other-than-human entities and elements create momentum for material exploration and creative production. These encounters are also sites for productive thinking about pressing ethical environmental challenges at the heart of making, which addresses our second question. The three methodological movements are threaded within the stories revealing how material-led research can aid researchers in attending to materials to provoke reflection and mobilize creative practice.

The first move, *attending to material assemblages*, is represented in all four stories as they emerge from unfolding and loose arrangements involving human and nonhuman entities. Story 3, following bodies in friction, offers a vivid example of how hands-gloves-mycelium assemblage disrupted the maker's dominant positionality. Ingold and Hallam (2014) note how it is often overlooked that "making is tough on bodies as well as materials" (p. 9). Together, the delicate fibers of mycelium form strong structures capable of wearing both the maker's body and the gloves after long periods of work. The physical draining of all bodies is evidence of the intense relationality characteristic of biomaking and most maker practices. When the gloves ripped, the practitioner also became aware of her intimate affair with the material world as she was unable to prevent her own microbiota from joining the other material flows that were "allowed" in the practice. The sight of the ripped gloves disintegrated the notion of discrete self and objective others and opened a new diffractive line of inquiry on the notion of contamination. Shotwell (2017) argues that "[t]o be against purity is […] not to be for pollution, harm, sickness, or premature death. It is to be against the rhetorical or conceptual attempt to delineate and delimit the world into something separable, disentangled, and homogenous" (p. 15). In biomaking, instances of contamination are ripe for learning and critical reflection on environmental challenges and underlying crises of human-nature relationship. Following unlikely and unwanted encounters and material tensions, the human body reveals itself as a series of nested assemblages of biotic and abiotic material bodies.

The second move, *noticing what materials do*, is illustrated by the first story, which follows hyphal threads at night. Looking through the camera into a place where nothing seemed to be happening led to an urge to uncover what was actually going on; all the bustling, jostling, breathing, and exuding that occurs in living worlds beyond our perception. It is often the case that things that seem unanimated are lively at other scales of time and space. Multidisciplinary documents, online videos, or specialized instruments can aid the process of unveiling their hidden but humming activity. This curiosity can be coupled with vigilant observation of what materials do over time. Transformations from one session to the next are particularly salient in biomaking but not unique to it. In other making practices, these changes are harder to discern but still present; clay cracks, batteries corrode, 3D printing filament becomes brittle, etc. Distinguishing those subtleties requires engaging with them through Tsing's (2015) "art of noticing" to discern how things may be entangled beyond their superficial appearance (p. 37). Directing novices' attention to material transformations can help them tune into their flows and respond to them accordingly. More importantly, it can bring awareness about the liveness of all material flows and their continuity beyond making practices.

The third move, *reading materials longitudinally*, is offered in all four stories through radically different longitudinal cuts given by the peculiar earthly timings of each material. In the first one, a short glimpse into the world of mycelium is enough to join the pulses and rhythms of microscopic worlds that continuously unfold beyond our sight. Conversely, the second story follows unruly encounters between vinyl and Ganoderma through deep time. Following lengthy earth cycles, we learn about how materials come into the relatively stable forms and consistencies we encounter today. This longitudinal reading reveals how seemingly contrasting bodies had long intermingled with each other, which diffracted speculative possibilities for unlikely materials to fold into each other back into terrestrial cycles. By attending to their ways of pacing through the earth, we learn to tune into material flows in both macro-geological and micro-biological timelines that unfold

beyond our field of perception and control.

Although examining our own making practices is a first step, a greater awareness of material flows and what they do can guide the development of more mindful making environments where educators and students are watchful of the whereabouts of their materials before, during, and after making. The three methodological movements bring into practice-based research an increased awareness of how making is mutually affected by material forces and reverberate through worldly tissues. Although this is patent when dealing with living materials, it extends to all our increasingly hybrid making practices, for even our most eccentric gadgets and elaborated forms of knowledge are rooted in our bodies and powered by the vitality of the earth. In our globalized civilization, what we make is too often severed from the matter that sustains it. Knowing where just one material comes from seems impossible in the artificial habitats where we spend most of our time. Giant corporations are intentionally secretive about the origins of the materials that feed into their large-scale making projects. The landscapes that forge their unique qualities are unknown and remote. Smooth and glossy electric cars haul rough elements from Altiplanic salt flats. We carry minerals gathered by young hands in Congo's rainforest disguised as smartphones in our pockets. We can even trace a palpable intimacy between ethereal forms of artificial intelligence and the human languages that feed its algorithms, the spoken tongues that still bear the texture of distant topographies in their words, sounds, and rhythms.

The above stories may not offer the comprehensive and systematic depiction of making procedures granted by traditional qualitative methodologies but rather reveal what we often fail to see when trying to describe our making practices. By following our materials, we realize their central role in provoking the ideas we call our own. Making becomes an exercise of thinking through the tissues of the world, and ecological and social implications become latent and hard to ignore. As educators, researchers, and makers, following materials can become part of our repertoire of design practices to re-ground maker education in a world that exceeds us.

(Un)concluding remarks

Material-led research is a methodology for makers and researchers in the learning sciences to study their own creative practices with keen attention to matter by attending to assemblages, noticing what materials do, and reading them longitudinally. Through a series of stories, we see how a material-led approach reveals biomaking and making as sites of productive material and intellectual inquiry. Material-led research is inherently exploratory, not to answer questions but to open them and nurture creative and critical practice with an ecocentric lens. As a methodology, material-led research can provide insights into the design of learning experiences and pedagogical methods for making in the Anthropocene. Fundamentally, it gives opportunities for considering how making practices are grounded in matter and how, as makers and educators, we can mindfully modulate our engagements with the living world.

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