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Embodied Learning in Makerspaces

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Abstract: Maker spaces (MS) are an emerging learning space, where students learn 'embodied' ideas and skills, which are different from those learned in theory classes and laboratories. Existing analysis of the nature of learning in MS is mostly descriptive. Here we seek to develop a cognitive account of the nature of learning in MS. We first outline two mechanisms from embodied cognition (EC) studies. We then illustrate how these mechanisms could advance our understanding of the 'building cognition' involved in MS, and the way it is extended by the making process. To illustrate the use of this analysis, we briefly outline the complex building cognition involved in three frontier making practices. We suggest that our EC analysis could help redesign MS in new ways, to support such making practices.

Keywords: Makerspaces, building cognition, tool incorporation, common coding, embodied learning, frontier making practices

1. Introduction

Embodied cognition (EC) is an emerging theoretical approach to model thinking and learning in new ways, focusing on the role of actions and the body in higher-order cognition processes such as discovery and innovation. In EC, cognition is modeled as extended into the environment, and the interactions between the body (including neural processes) and external structures are considered as *constituting* (i.e. bringing into being) cognition and learning. Makerspaces (MS) offer a promising site to systematically study the nature of embodied cognition and learning, as the situated-in-the-world nature of activities in MS provides good opportunities to analyze embodied thinking and learning.

In this paper, we examine how EC models could help understand the ways in which MS advance student thinking, and how this analysis could be extended to align MS practices with contemporary innovation practices. This two-fold characterization could help integrate MS with existing pedagogical theory, policy and curricula, and also contemporary innovation practices. Section 2 outlines the makerspace literature and the EC knowledge gap. Section 3 discusses two candidate EC mechanisms to analyze MS. We then extend the existing analysis in the literature using these mechanisms, to develop a preliminary framework to understand the nature of embodied learning in MS. Section 4 briefly sketches a three-tier framework to understand making practices at the frontiers, which have features that are not supported by current MS practices. We conclude with a brief discussion of how these components could in principle be supported by MS practices.

2. Making and Learning: The Studies So Far

Efforts to characterize makerspace practices are still in the early stages, as MS practices and context are highly diverse and still evolving. Given the dynamic and varied making environments, the rapidly evolving practices, and the proliferation of in-school makerspaces, MS practices are challenging to conceptualize and study. Theoretical approaches like constructionism, multiliteracies, and communities of practice (CoP) have been used to understand learning in MS.

2.1 Makerspace and Maker Movement

Sheridan and colleagues (2014) define makerspaces as "informal sites for creative production in art, science, and engineering, where people of all ages blend digital and physical technologies, to explore ideas, learn technical skills, and create new products." MS is interdisciplinary, and can support projects that combine a wide range of domains, such as woodworking, electronics, cooking, painting, robotics, textile craft (Peppler & Bender, 2013). The proliferation of MS is fueled and supported by a broader movement, a growing intergenerational community of hobbyists, tinkerers, crafters, hackers, or any individual who resonates with the "do-it-yourself (or do-it-with-others) mindset" and finds "physical and digital forums to share their processes and products with others" (Halverson and Sheridan 2014:497; Peppler & Bender, 2013).

The maker movement as we know it now has emerged in the last 15 years. The first maker faire was organized in the Bay Area, USA in 2005, and saw participation from a wide range of professions, and showcased varied projects. The faire seeded a sense of shared community identity that transcends disciplines (Bevan, 2015). Physical spaces in the form of Fab Labs, Makerspaces, Techshops, Tinkering studio etc., along with periodic Maker Faires, and diverse online communities of practices, have led to widespread popularity for making as a practice. This has also attracted various stakeholders in the education space - researchers, educators, school administrators and policymakers. One of the largest in-school programs to set up a network of tinkering spaces – Atal Tinkering Labs (ATL) – was initiated by the Government of India in 2016. This has led to the setting-up of 7000+ dedicated maker spaces within schools (AIM, n.d.).

2.2 Making in Education

Blikstein (2018) reconstructs the history of the maker movement in education, and discusses five societal trends that led to the current shift towards making. The first trend is a greater ‘societal acceptance’ of ideas proposed by progressive educators and scholars, such as Dewey (1902), Montessori (1931), Freire (1970) and Papert et al., (1980), arguing for educational experiences that are personally meaningful and authentic. To design such classroom experiences, these approaches foreground the following as core principles: material-based investigation, valuing learner’s voices, and tapping into learners’ cultural resources. Making provides a natural context to instantiate these ideas cohesively. This has led to MS gaining greater acceptance in education circles.

The second trend is related to countries competing to get an innovation edge. To support a creative and flexible workforce a radical redesign of the education system is needed. Makerspace is generally associated with early adopters of new technologies and tools, and is seen as a fertile ground to seed innovation. Other related trends include the rapidly growing popularity of coding and making, affordability of digital fabrication and physical computing technologies, the open-source movement, and accessibility of carefully designed MS learning environments. These factors together have lowered the barrier for participation, allowing novices to build sophisticated and shareable artefacts. These features have also created conducive conditions to bring making into formal school settings.

2.2.1 Classroom, Laboratories, and Maker spaces

The traditional classroom, and its didactic instructional approaches, have been critiqued by educators and scholars (Illich, 1971; Freire, 1984). The one-size-fits-all curriculum, age-based segregation of students, and a skewed focus on 'content' – which favors abstract and procedural knowledge – promote pedagogical strategies and assessment techniques that value only formal reasoning.

Laboratories do emphasize material-based investigation, but with a strong focus on conceptual connections to theory. They also provide an opportunity to develop fluency in scientific practices (Miller, 2004). But laboratory practices are critiqued for providing only limited trajectories of exploration. People work on "known solved problems", which have a tight coupling to the curriculum. Lab work often does not privilege local experiences and expertise (Osborne, 1993; Lunetta, Hofstein, & Clough, 2007). Lab handbooks mostly have a cookbook style of instruction, laying down the exact method, procedure and protocols to adhere to, while doing experimentation.

Maker culture, on the other hand, focuses on personalization, allowing people to work on things they care about, and collaboration. Peer learning in various forms is generally observed in this space, through shared expertise that leverages others’ learning experiences, or others sharing their anecdotal breakthroughs after getting “unstuck” (Petrich et al., 2013; Bevan et al., 2015). Making as education practice does not have a fixed curriculum, and the role of the teacher is that of facilitator, providing constructive feedback to the learners (DiGiacomo & Gutiérrez, 2016). Also, making is considered to engender the culture of creativity and intellectual risk-taking, valuing materials-based investigation and tinkering. Scientific concepts and phenomena are recruited in the context of construction, but towards achieving specific tasks, while working on virtual/physical artefacts (Bevan, 2017). Free flowing, organic, and informal styles of investigation and documentation are embraced.

These features position MS as a unique learning environment, *different from traditional science classrooms and laboratory spaces*. However, while there is a large literature on the nature of learning in theory classrooms, with consensus on cognition constructs such as transfer and conceptual change, similar analysis does not exist for the nature of learning in MS, or laboratories. This is possibly because of the critical role EC plays in both, which makes such analysis very difficult. We examine below some analysis constructs developed for MS.

2.2.2 Making as design and engineering practice

The Table below summarizes a set of constructs used by scholars to characterize maker practice.

Table 1. *Existing Characterizations of Maker Practice*

Construct | Citation	**Summary**
Creative and intellectual risk taking | (Bevan, 2017; Peppler, 2016)	MS is seen as a powerful context to foster creativity, due to its multidisciplinary nature of engagement. The iterative nature of the process re-frames failure as opportunity to learn, thus encouraging risk-taking.
Productive STEM identity | (Quinn & Bell, 2013; Bevan, 2017; Buechely, 2008; Kafai, 2010; Peppler, 2013)	Making dispositions and competencies are associated with practices and knowledge in science and engineering; making also has the potential to appeal to those who don't identify as STEM learners, thus fostering productive STEM identity; making provides an alternate authentic way to engage in science concepts. This challenges the currently dominant 'deficit' models of engagement.
Personalization | (Blikstein, 2013; Martin & Dixon, 2013)	Makers often work on things they care about, incorporating expressive ways to use technologies, connecting them to everyday experiences.
Iterative prototyping | (Vossoughi, Escudé, Kong, & Hooper, 2013; Tseng, 2016)	The journey of building project from ideation to prototyping is often non-linear and iterative; provides opportunity to deepen the relationship with materials, tools, techniques; develops fluency in scientific concepts; makes documentation process-based, rather than product-based.
Playful experimentation | (Regalla, 2016)	Playful experimentation is frequently observed in MS setting, during tinkering, building prototypes, exploring tools and materials.
Feedback | (DiGiacomo et al., 2016)	Making and tinkering opportunities create necessary conditions that allow learners to receive feedback in a "repair-friendly" way, encouraging further experimentation and intellectual risk-taking.
Collaboration-through-air | (Halverson et al., 2018; Litts, 2016; Kafai & Harel, 1991)	Collaboration in maker-centered settings is generally seen as feature of the learning environment. Halverson et al. (2018) takes an emergence stance to collaboration, and found that often ideas, tool-use and techniques are floating in the space, ready to be "picked up" unpredictably, without "explicitly coordinated goals" during open-ended making activity.
Productive failure | (Blikstein, 2013; Martin, 2015)	Maker centered settings often celebrates failure as a desirable outcome. It is posited as a productive heuristic, to iteratively help revise and deepen understanding at various stages during the design process, such as while testing ideas or experimenting; uncovering mechanism (Blikstein, 2013).
Drafts | (Vossoughi et al., 2013; Vossoughi & Bevan, 2014; Vossoughi et al., 2016)	Characterizes failure as "drafts" which can be revised based on feedback. Encouraging drafts as a way to externalize ideas; exploring design decisions and seeking constructive feedback renders maker-centered practice more meaningful, foregrounding the importance of process over the final product.
Connecting to local culture | (Calabrese-Barton & Tan, 2018; Fields & King, 2014; Vossoughi et. al., 2013)	Role of lived experiences and local knowledge to design meaningful learning opportunities. Tap cultural resources to broaden the STEM participation.
Informal documentation | (Peppler, 2013; Vossoughi et al., 2013)	Documentation (analog/digital) is considered an important aspect of making practice. It plays a key role in mediating and nurturing a meaningful relationship with the community. An example is an after-school educator using journaling as an analogue way to capture the process of making. The journal

Construct | Citation	Summary
	was positioned as a tool "for time travel, idea-creation and memory".
Conceptual learning | (Peppler 2013; Blikstein, 2013; Wohlwend et al., 2016; Brahms & Crowley, 2016; Kafai, 2014)	Increased understanding of key circuitry concepts when participants were engaged in activities related to e-textiles. Findings indicate that the conversation among youth makers while designing becomes increasingly complex, integrating physics vocabulary. Despite the 'rhetoric about making' as supporting conceptual understanding, in-depth research is scarce (Bevan 2017).
Adaptive expertise | (Martin & Dixon, 2016; Blikstein, 2013)	Adaptive expertise is fostered by dialogues during making activity. Experts recruit deep conceptual knowledge; attempt to solve unexpected challenges and innovate.
Identifying, organize, and integrate | (Gravel et al., 2018)	Design principles that could support young makers' trajectories in formal setting. For example, experts engage in identifying, organization and synthesis of information from disparate sources.
Taking up leadership role | (Buchholz et al., 2014)	The nature of materials and activities can have implications on forms of participation across gender. STEM-rich making that integrates materials can appeal to boys and girls, and thus challenge the deficit view.

2.3. The Knowledge Gap

This short review shows that the literature on MS does not provide an analysis of: 1) the various ways in which actions and the body advance learning based on MS environments, and 2) how this process could lead to new forms of embodied learning. The next section outlines a preliminary framework, based on two cognitive mechanisms, to understand the nature of embodied learning supported by MS.

3. Possible cognitive mechanisms involved in maker practice

Most analysis of MS are descriptive, and do not focus on the cognitive mechanisms that are involved in MS practices. A cognitive analysis could help characterize the MS equivalents of transfer and conceptual change, and thus make clear how MS practices advance student learning. In the following section, we discuss two possible cognitive mechanisms that could provide such an account. We then discuss how embodied learning in MS could be understood based on these two mechanisms.

3.1 Tool Incorporation

Cognitive neuroscience studies have shown that tool use extends the body schema. Users 'incorporate' the tool into the body (for a review, see Maravita and Iriki 2004), and this incorporation extends the imagination capacities of the tool user. A good example of this is provided by Iriki et al (1996), who examined the firing of bimodal neurons (in the intra-parietal cortex) before and after a monkey learned to use a stick to gather food. These neurons fire when the monkey's hand is touched, as well as when a light is flashed on the hand. Interestingly, this firing happens when the light is flashed not just on the hand itself, *but also in the space close to the hand* (the 'peripersonal space'). The neurons thus code for the 'action space' -- the possibilities for activity -- rather than just the hand.

Iriki et al. (1996) examined whether this firing pattern changed once the monkey started using a stick as a tool. This investigation was done in three phases (see top panels, Fig. 1, adapted from Maravita and Iriki 2004). In the first phase, there was no stick, and the light was flashed on and near the hand, and the bimodal neuron fired. In the second phase, the monkey passively held the stick, and the investigators flashed the light near the monkey's hand, as well as at the end of the stick. The bimodal neuron fired only when the light was flashed near the hand. In the third phase, the monkey used the stick to retrieve food, from a location that was not reachable by its hand. Immediately after this intentional action, the investigator flashed the light on the hand as well as at the end of the stick. The bimodal neuron now fired for light flashes *near the hand as well as at the end of the stick.* This result showed that the peripersonal space (the area of possible activity coded for by the neuron) was now extended, to include the area covered by the stick (bottom panels, Fig. 1).

The intentional action led to the stick being incorporated into the body, and the monkey's peripersonal space (space of possible activities) now extended to the entire area, and objects, reachable by the stick. This extension of peripersonal space is important, particularly for MS, as it shows that such incorporation is not just about adding an external entity to the body schema. Incorporation expands *the range of possible activities* the monkey can do, *and imagine* — in terms of location of activity, other entities involved, nature of activity, the number of activities, and the permutations and combinations of activities. This expanded range also extends the monkey's understanding/knowledge of the stick, as well as the space around it, which is now understood in relation to the stick. The monkey's cognitive capacities, and problem-solving abilities, are thereby expanded. Similar incorporation of external entities occurs in humans as well (Farne et al. 2005).

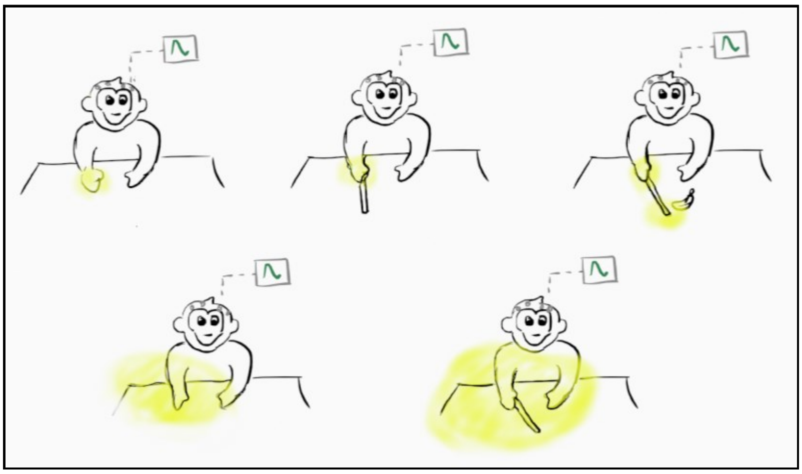

Figure 1. Tool use extends the body schema and the peripersonal space.
Figure based on Maravita & Iriki, 2004; image credit: Ravi Sinha.

3.2 Common Coding

Recent research in cognitive science and neuroscience shows that when humans perceive and imagine movements, particularly actions, their motor system is activated implicitly. In the other direction, execution of movements improves perception and imagination of movements. This three-way movement connection is explained by the common coding hypothesis, which proposes that the perception, execution, and imagination of movements share a common representation (common coding) in the brain. First articulated clearly by Prinz (1992), and later supported by the discovery of mirror neurons (Di Pellegrino et al., 1992), this common neural code allows any one of these movements to automatically trigger the other two movements (Prinz, 2005; Sebanz, Knoblich, Prinz 2005; also see Decety, 2002; Hommel et al, 2001). One outcome of this common coding is a body-based "resonance" – the body instantly replicates all movements it detects, generating an *internal representation* of the movement. This replication creates a dynamic trace, based on body coordinates, which can play a role in later cognition.

Building on this model of common coding, recent approaches propose that actions are controlled using "internal forward models (predictors) that emulate the dynamic behavior of our body and environment, thereby capturing the forward or causal relationship between our actions and their consequences" (Schubotz, 2007). The idea of forward models (Wolpert & Kawato, 1998) suggests that *all actions involve a minimal imagination* element, which seeks to predict the consequences of the action. This minimal imagination system acts as a seed process, to develop more full-fledged imagination of movements. Interestingly for the MS case, this seed imagination (forward model) can run *independent of actions*. This 'off-line' process contributes to motor imagery, estimation of outcomes of different possible actions, and evaluation as well as development of motor plans (Grush, 2004). Forward models are also considered to have a role in the estimation of dynamic properties of manipulated objects (Davidson & Wolpert, 2005).

Important for our purposes here, Schubotz (2007) proposes that forward models are used to predict movements of inanimate objects (such as waves on a beach) and serial events (such as sequential moves in a problem-solving task). For this, the brain automatically activates the closest forward model to the movement that is perceived. This closest model, activated in a resonance fashion, is then tweaked, based on input from the perceptual system, to make predictions about the encountered inanimate movement. Given the common coding between execution, perception and imagination of movements, the above principles (resonant activation of closest forward model, prediction based on perceptual feedback, revision of forward model) would also apply to 'off-line' action (imagination), of inanimate object movement and serial events.

3.3 Embodied Learning through MS practices

How do these two mechanisms allow us to develop a cognitive account of learning supported by MS practices? To briefly illustrate this, we discuss how four features of MS (Iterative prototyping, Playful experimentation, Feedback and Collaboration-through-air; see literature review) are supported by these cognitive mechanisms. Further, we also discuss how the cognitive mechanisms change through this process, and how this leads to different kinds of embodied learning.

Iterative prototyping: As discussed, tool use leads to the tool becoming part of the user's body schema, and thereby extends their possible action space. However, based on the incorporation and forward model mechanisms, it is not just the action space, *even the imagination of the action space* is altered by actions with the tool. This suggests how tools allow 'thinking with tools'. Extending this, iterative prototyping can be seen as a way to 'think with prototypes'. Building each prototype leads to the prototype getting incorporated. The resulting extension of the maker's body schema leads to an extension of their imagination of possible making actions, in the 'prototype space'. This extension of imagination 'mutates' the space of possible prototypes, to generate further making. Prototyping thus creates a chain of embodied learning and imagination.

Playful experimentation: The same process would be involved in playful experimentation, which could be seeded by the incorporation of the previous prototype. The extension of the imagination (by the incorporation process) would generate many possible branchings of the making space. The playful experimental advances can be seen as tentative external manifestations of these branchings, which are not fully formed. Interestingly, makers need to learn to control these branchings, and select which experimentations are productive. This requires the emergence of an evaluative neural network, to prevent a runaway imagination process. The development of this evaluative module is a key embodied learning effect of MS, not possible without the building of prototypes and the playful experiments.

Feedback: The systematic feedback in MS practices also allow the making imagination to be extended. However, this process is driven by others' imagination processes, based on incorporation of similar/related prototypes they have built. This creates overlapping making spaces in the imagination, which allow couplings to form, between the maker's and others' imagination. Such 'recombinant enactions' (Rahaman et. al., 2017) generate new making spaces, and thus embodied learning.

Collaboration-through-air: Finally, the Collaboration-through-air feature (*'ideas, tool-use and techniques are floating in the space, ready to be "picked up" unpredictably, without "explicitly coordinated goals" during open-ended making activity'*) can be understood as an effect of the 'resonance effect' supported by common coding and forward models. In MS practice spaces, makers would resonate each others' actions. This leads to a minimal ability to replicate others' use of tools, and prototypes. Such implicit replication leads to the ability to mimic and follow others' imaginations, based on stored traces of this tacit resonance. In combination with incorporation of their own prototypes, these resonances would lead to new ways of combining their own making space with others' practices. These new branchings in the making space could lead to actions, or imaginations, that others resonate with, as these actions/imaginations naturally extend their action spaces. Such extensions create joint action spaces. These lead to collaborations-through-air, tacitly combining different groups' making practices, without anyone explicitly promoting such collaborations.

This (admittedly dense) outline provides only a sketch of how EC mechanisms could be used to understand the way MS practices lead to a 'building cognition' (Chandrasekharan, 2009; Chandrasekharan, 2014; Chandrasekharan & Nersessian, 2015), and resulting embodied learning. A richer account of this process is under development, extending previous work on building cognition. This discussion also examines how current MS practices are related to frontier making practices.

4. MS as a sandbox for frontier making practices

We present three frontier making practices, and discuss how they are different from MS practices.

4.1 Tier 1: Engineering Sciences

A key making practice at the frontier is engineering sciences, where practitioners seek to combine physical building processes with mathematical modeling processes -- to fuse together biological, electrical and mechanical systems. Examples include the design of artificial biological systems, such as artificial heart, biorobots, neural engineering, and metabolic pathways (Nersessian & Patton, 2009; Chandrasekharan, 2009). Another focus area is the development of fuel cells and biofuels (Chandrasekharan & Nersessian, 2015). Such making integrates modeling actions, fabrication processes, complex lab activities, experiments, persons, and equipment. Building microfluidic lab-on-a-chip devices present a good example (Aurigemma et al., 2013), where the design involves building many prototype systems (physical models) and simulations (computational models) and integrating their results in various combinations, to arrive at a final prototype.

Such making is at the frontier, because it builds for, and generates, new discoveries. A key difference between this type of frontier making practice and MS practice is the way it combines theoretical computational models for scientific discovery with the making of novel reality -- systems that 'act out' new world states. For this, novel scientific ideas are embodied/enacted using both prototypes and computational simulations, and the results triangulated, or played off against each other. This requires integrating mental models, computational models, prototypes, and different lab methods. Recent theory (Chandrasekharan, 2009; Chandrasekharan, 2014; Chandrasekharan & Nersessian, 2015) argues that this building cognition is also driven by 'incorporation'. However, this EC process is more complex than the one we sketched for MS practices.

4.2 Tier 2: Socio-Technical Engineering Sciences

A more complex version of engineering sciences seeks to drive making through social and economic factors. This practice demonstrates the critical role problem formulation plays in innovation. It also illustrates the integration of the social and the technical, which is usually missing in MS practices.

A good example of this is the recent development of the 'paperfuge' (Bhamla et al., 2017) – a low-cost hand-operated centrifugal machine for testing blood, to address the problem of limited electricity access in medical labs in Africa. The design used microfluidic technology, and also discovered a novel scientific result – that the RPMs achievable by hand are much more than previously thought. The design/discovery started from a social need, developed a real-world application based on a cutting-edge technology, and contributed to the science of rotation. This design approach widens the making space, bringing in social needs and constraints as ways to mutate the making space, and thus drive innovation. This approach is currently missing in MS practices.

4.3 Tier 3: Eco-Socio-Technical Engineering Sciences

A more complex frontier practice seeks to redesign of the practice itself, to address climate change (which is driven by making), and promote a sustainable and equitable way of life (Date et al., 2019). Many cases of such designs share the spirit of MS, but the scale is much wider, and the stakeholders highly disparate. It is unclear how MS could be adapted to meet these requirements.

A good example of such making is the case of Danish wind technology. During the 1970 energy crisis, many countries struggled to develop wind technology as a source of power. Among these efforts, the Danish wind turbine systems proved to be the most successful, despite the high-tech competence and high capital investments of other countries. Importantly, this success came from a novel socio-technical process, an early precursor of sustainability engineering. The making started with Johannes Juul, a Danish electrician, who had built a 200 kW wind turbine in Gedser, Denmark in 1957, which ran successfully for ten years. Based on this turbine, and Juul's designs, carpenter Christian Riisager and blacksmith Karl-Erik Jørgensen started building simple wind turbines.

> *"Riisager assembled his first wind turbines from inexpensive off-the-shelf parts, such as standard asynchronous generators and truck gears, axles, and brakes. In spite of his limited theoretical background and experience, by 1976 Riisager had produced a surprisingly reliable 22-kilowatt turbine." (Karnoe, 1978 cf Heymann,*

1998). "By January 1978 he had sold six copies; within the next two years he sold fifty more." (Heymann, 1998).

Heymann (2015) notes that in their craft-like method, "Practical experience turned out to be a key advantage. It gave rise to a rich base of personal 'tacit' knowledge, a feeling for forces and loads and for the performance and limitations of technical components." Kamp (2008) points out that the design process of small-scale entrepreneurs is guided by 'learning by doing, using, and interacting', while that of the R&D institutions is by 'learning by searching'. Karnoe (1990) argues that the Danish process was bottom-up (and thus similar to MS), following a step-by-step process based on incremental learning, through practical experience. However, it used many different knowledge bases (both theory and craft) and this created different orientations, values, mentalities and ideologies, which needed to be managed. Craftsmen were conservative, while theoretically trained engineers exhibited ambition for innovation and confidence, but under-estimated the challenge. Both had to work with policy makers, who had other priorities. Managing such conflicts is critical to the success of this type of frontier making practices. It is unclear how MS practices could support these factors.

5. Conclusion

The above three-tier framework presents a brief sketch of how frontier engineering practices, for which MS could be a sandbox, is critically different from current MS practices. However, as noted, frontier practices can also be understood as building cognition, based on EC mechanisms such as incorporation and prototype-based imagination. A detailed analysis of embodied cognition in MS could thus allow MS practices to be systematically extended, to support the novel building cognition involved in frontier making practices. We hope our brief discussion of EC mechanisms in MS, and the way frontier making practices extends these, initiates a conversation on how frontier practices, and the building cognition they require, could be supported by MS.

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