RESHAPING MAKERSPACES TO LEARN FRONTIER MAKING PRACTICES

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School-based makerspaces (MS) offer potential spaces for learning frontier engineering design practices, which could enable students to address current and future societal needs and challenges. In order to explore how school-level MS could be reconfigured to scaffold the learning of frontier engineering design practices, we describe the design process of a frontier making case (Paperfuge). We extract the key engineering design practices in this case, and represent them as an expanding spiral pattern of the design space. We argue that this pattern (shown also in other cases) suggests ways to integrate key frontier making practices into MS. We briefly discuss some of these ways with respect to the current MS pedagogy.

INTRODUCTION

Makerspaces (MS) are building, tinkering, and learning spaces where people from diverse backgrounds work on collaborative or individual projects, learn new skills, hang out with friends, or repair things (Peppler et al., 2015; Vossoughi & Bevan, 2014). Many community-MS also have fabrication technologies such as 3D printers and laser cutters, which allow teams to work on hardware prototypes or even manufacture products in small quantities (Anderson, 2012; Blikstein, 2013; Mersand, 2021). Several companies, colleges, and K12 school settings have on-campus MS, and the Indian government has initiated an ambitious Atal Tinkering Lab (ATL) program, seeding over 7000 tinkering spaces for middle and high school students, with INR 20 Lakhs per school, (approximately 18 million dollars in total) in grants (AIM, NITI Aayog, n.d.). ATL aspires to enable making that addresses the current and future unmet needs and challenges of society (AIM, NITI Aayog, n.d.).

There is a growing interest among policymakers, educators, and researchers about the potential of MS to provide alternate and diverse pathways for building productive STEM identities. Additionally, MS is viewed as a testbed for innovative and emerging ideas, with the potential to foster STEM learning and nurture "neoteric innovators". Researchers have characterized MS practices using constructs such as collaboration through the air, iterative prototyping, feedback, and playful experimentation (Bevan, 2017; Halverson & Peppler, 2018; Mersand, 2021; Sheridan et al., 2014; Sinha et al., 2021; Vossoughi & Bevan, 2014).

As MS supports material-based, hands-on activity, and artifact-building through iterative prototyping, it is a potential space for learning frontier engineering design practices. Recent research argues that learning of practices is as important as learning the body of STEM knowledge (Fields et al., 2017; NRC, 2012). The National Education Policy (MHRD, 2020) emphasizes “Experiential learning within each subject, and explorations of relations among different subjects (p 11)” at Middle and Secondary education stages. It also encourages curricular integration of ‘Essential Subjects, Skills, and Capacities’, including innovativeness, problem-solving, and design thinking (p 15). However, it is unclear how school-level MS could be configured to scaffold the learning of frontier Engineering Design practices.

This paper presents an initial exploration of how school MS (such as ATL) can support the learning of frontier making practices. For this, we first describe the design process of a frontier making case (Paperfuge), which addressed unmet social needs. We extract the key engineering design practices in this case, and represent them as an expanding spiral pattern of the design space. In the discussion section, we argue that this pattern (shown also in other cases) suggests ways to integrate the characteristic frontier making practices into MS, and discuss these with respect to the current ATL-MS pedagogy. We conclude with the potential implications of this analysis for MS researchers, educators and designers.

DESIGN OF THE PAPER CENTRIFUGE FROM PRAKASH LAB

Paperfuge is an ultra-low-cost (20 cents), lightweight (2g), portable, human-powered centrifuge made out of paper, string, and plastic, designed by Saad Bhamla and colleagues in the Prakash Lab at Stanford. A vial of blood sample is attached to the rotating paper disc, like the one in a whirligig/ buzzer toy (see Fig 1 (right)). It can help perform several diagnostic assays, like separation of plasma from blood, to detect diseases like malaria. The design of Paperfuge led to innovations in point-of-care diagnostics, and also generated new theoretical knowledge (analytical solution for the whirligig/buzz toy dynamic system). The design originated from the team's serendipitous encounter with an expensive centrifuge used as a mere door-stopper in a remote health clinic. Since the clinic did not have stable electricity, the centrifuge machine, though needed, could not be put to its designated use. Manu Prakash's team, having designed an ultra-low-cost microscope earlier, decided to tackle the challenge of designing a portable, ultra-low-cost centrifuge that does not require electricity (TED, 2017, 03:18; Rober, 2017, 5:54). We describe the design process as a series of episodes.

Episode 1

As the centrifuge works by spinning, the team began by investigating everyday gadgets such as salad spinners, yo-yos, and egg beaters, among other things, as possible starting points for the design. A closer examination of the feasibility of the solution, based on the requirement for high RPMs, revealed that the whirligig toy may be a potential choice. The other options were bulky, and had low RPM outputs that made the separation time impractical. This led to a preliminary centrifuge design that was a modified whirligig/ buzzer toy (Bhamla et al., 2017:3). According to Saad Bhamla, "This is a toy that I used to play with when I was a kid. The puzzle was that I didn't know how fast this would spin. And so, I got intrigued, and I set this up on a high-speed camera. And I couldn't believe my eyes. This thing, when you heard the noise, was actually going at 10,000 to 15,000 RPM. To me, that seemed like what we wanted to actually make a centrifuge." (Stanford, 2017).

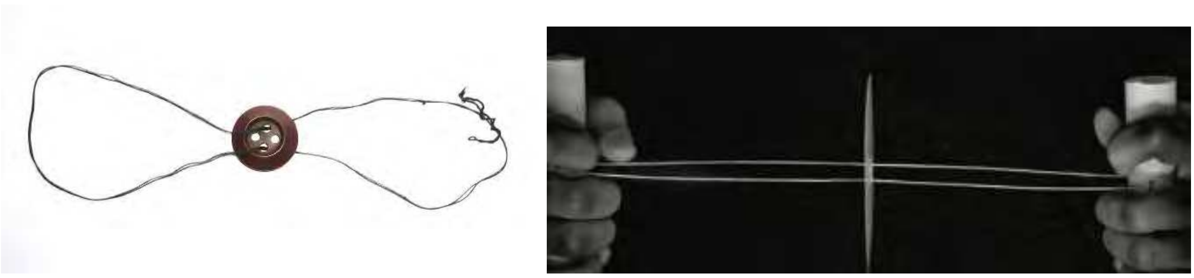

Fig 1 (left) Traditional button whirligig (Wikimedia); (right) Paperfuge (Bhamla et al., 2017)

Episode 2

According to Manu Prakash, "Before us, nobody had actually understood how this toy works. So, we spent a significant portion of this time truly understanding the mathematical phase." (Stanford, 2017). The team developed a detailed theoretical model capturing the extensive parameter-space of the whirligig system. With a disk diameter of 5mm, they were able to achieve 120,000 RPM and 30,000 G forces, for a mathematically calculated RPM of one million. Using experimental data to validate this model allowed them to optimize the dimensions of the components. With a disk diameter of 50 mm, their paper centrifuge spins at 20000 RPM and 10,000 G forces (Bhamla et al., 2017).

Episode 3

Unlike conventional centrifuges that rotate unidirectionally, this design uses a string mechanism, making it an oscillatory system. Rigorous experimentation was conducted to develop custom protocols for different types of assays, to validate the design efficiency and reliability of the buzzer-centrifuge model, as compared to the off-the-shelf standard centrifuges. Bhamla, Manu Prakash, and colleagues (2017) mentioned that the ratio of plasma and blood after spinning for 90 seconds proved to be sufficient to calculate the hematocrit value (that tells whether someone is anaemic or not). Additionally, spinning the Paperfuge for 15 min can separate the buffy coat and can isolate malaria parasites (Bhamla et al., 2017).

Episode 4

The design was improved by incorporating three independent mechanisms to avoid spills during operation. Firstly, the disk had a sandwich model, sealed via Velcro strips to avoid the spill of blood from the capillary at high speed. Secondly, the capillary was chosen to be extremely durable and able to withstand high G forces. Thirdly, capillaries were inserted into "sealed-straw holders" to further avoid accidental leaks. (Bhamla et al., 2017).

Episode 5

The Paperfuge design was replicated with materials other than paper, such as wood and polymer. These were 3D-printed, and explored for applications such as the separation of nucleic acid, DNA etc. Additionally, this process opened up novel avenues to design point-of-care (POC) diagnostics instruments that are versatile, extremely portable, and low-cost. The 3D-printed design is also manufacturing-compatible, as it can be made in large numbers using the conventional injection-moulding techniques.

CHARACTERIZATION OF THE PAPERFUGE DESIGN PROCESS

Based on this reconstruction of the Paperfuge design process from secondary data, we now extract the salient features and practices characteristic of this frontier making practice. Within and across these design episodes, the design process was iterative, and nonlinear.

Problem formulation started with identified unmet need in a particular social context

The team was involved right from *the stage of identifying the social need in its context*, and *formulating the problem that needed to be solved to address this need*. This led to a completely novel design, and not a mere customization of the existing centrifuge machines.

Contrary to this, if the design process had started with theoretical studies of the buzz toy as a dynamic system, and sought to maximize its efficiency, it is possible that a hand-powered centrifuge for medical diagnostics would have never happened. (In an extreme scenario, the optimization would have led to a new weapon design, given the force it can generate.)

Optimization approach in Paperfuge

It is possible that battery-driven portable centrifuge machines could have been designed to address the electricity constraint. But the Prakash lab imagined the Paperfuge functioning in a severely resource-constrained environment, and aimed for a simpler design without batteries. While optimization is usually focussed on efficiency, where the input is minimized, and/ or the output is maximized, the Paperfuge optimization focussed on fitting the available (hand-powered RPM) input to achieve the required output (separation of fluids) by developing time protocols. Performance optimization here was oriented towards and driven by the requirements, and was not a purely techno-scientific efficiency maximization.

Spirally expanding problem scoping

The initial identified need was to spin without electricity. Progressively, the prototype solutions allowed identifying other requirements – time and safety protocols, appropriate capillaries, and manufacturing processes that served the context. These requirements were not purely techno-scientific, and the socio-economic aspects of the context were integral to them. It was probably not possible to identify all the diverse socio-technical requirements in one go and develop a solution. Within every problem-solving episode: i) a need was identified, thus scoping the problem at that level, ii) a complete solution was developed, iii) a broader need became apparent from the prototype, thus expanding the scope of the problem, iv) the prototype was modified to develop a solution to the expanded problem, v) the process continued, to identify more complex socio-technical needs and to design satisficing solutions.

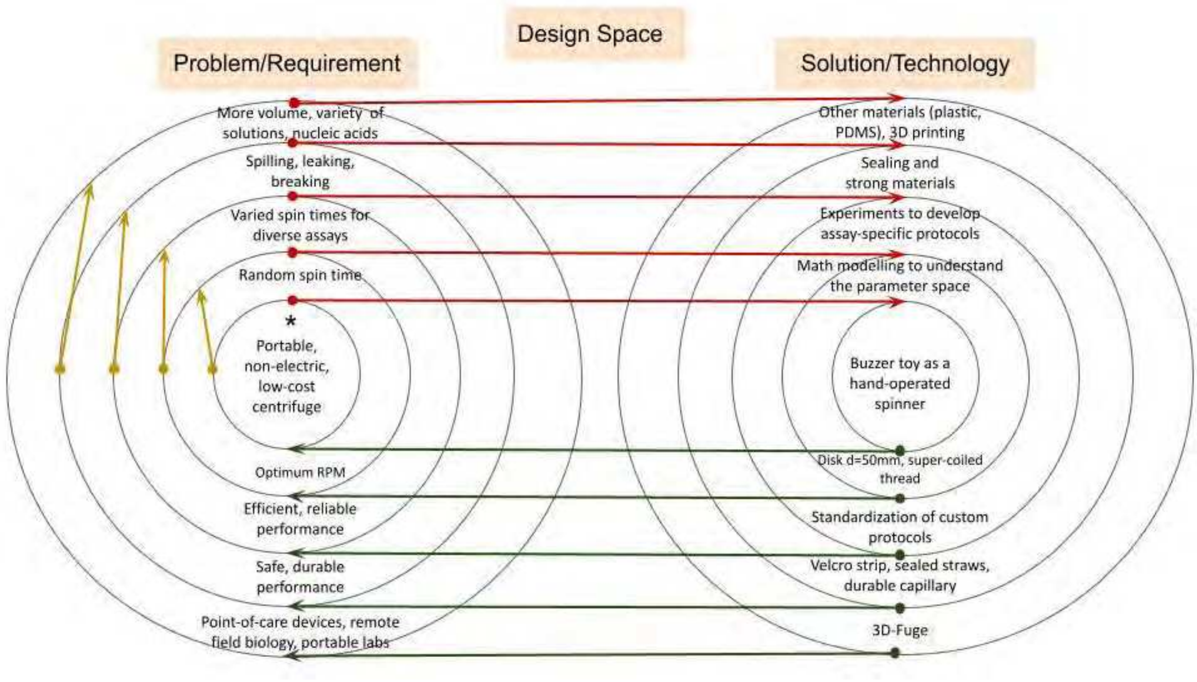

Fig. 2: The expanding spiral pattern of Paperfuge socio-technical design. Left: the problem (top), requirements met (bottom); Right: the solution (top), the technology (bottom). The

spiral starts at the '*' in the left core circle, and traces the arrow sequence Red-Green-Yellow.

Figure 2 represents this process. The design episodes, starting with the first episode at the core of the concentric circles, depict the identified need in the 'problem/ requirement' space, and the corresponding technology design in the 'solution/ technology' space. The solution feeds into the next need identification, starting an expanded version of the next episode of the problem-solution cycle, and so on. We call this the *expanding spiral pattern of design* space and process. The spirally expanding process allowed for a step-by-step experiential understanding of the solution, in terms of its functioning and performance. It also revealed requirements yet un-addressed by the solution, thus leading to a new innovation cycle in an expanded design space.

Contribution to theoretical understanding

The team, though trained in advanced engineering sciences and modelling techniques, did not start the design process with the theoretical/ formal structures or exact calculations. The design direction was the reverse, with *theoretical understanding extended by the prototype*, in the process of creating one of the fastest spinning human-powered gadgets (Bhamla et al., 2017).

Product and manufacturing are co-designed

Using injection-moulding techniques expands the design space to include mass-manufacturing of the 3D-fuges (3D-printed fuges made of polymers). This allows manufacturing considerations to be a part of the design process, and to manufacture the product independent of any constraints imposed by pre-existing capital-intensive manufacturing facilities. The designers "move all the way from gathering requirements to developing specifications to product design and manufacturing design" (Date & Chandrasekharan, 2018).

DISCUSSION

About their unusual Paperfuge design journey, Manu Prakash says "There is a value in this whimsical nature of searching for solutions because it really forces us outside our own sets of constraints" (Stanford, 2017). Frontier making, where solutions at the cutting edge of science and technology are built, requires stepping outside established engineering, mathematics, labs, factories, manufacturing and business structures.

If makerspaces are to be places where students learn engineering design practices that enable them to do this kind of frontier making, it would not suffice for makerspaces to function around a 'toolkit' idea of activities, where students start by learning tools or techniques and end by building what can be built with those tools or techniques, leading to a prototype (mostly proof-of-concept) for a narrowly construed problem statement. Instead, makerspaces need to be places that support students in (ad)venturing out of their classrooms and labs to notice a requirement, and formulate it into a problem they can solve by making, even if it requires devising new tools, techniques, and conceptual knowledge. To do this, makerspaces such as Atal Tinkering Labs may need to expand their purview and pedagogy.

The expanding spiral process of the Paperfuge design, and other similar models reported elsewhere (see Date & Chandrasekharan, 2018, for other examples), indicate that: a) identifying and designing for a primary need comprehensively, and then widening the scope of the need to be addressed, is a key approach to problem-scoping in socio-technical design processes, which is needed to address complex and messy problems; b) eco-social factors can enter the design space, simultaneously with techno-scientific considerations and not later as add-ons; c) multiple cycles are not random explorations, rather the designed prototype/ solution plays a role in the next design episode or cycle.

CONCLUSION

Drawing on this characterization of frontier making, school-based makerspaces could encourage students to identify needs by themselves, rather than work with a given problem statement. If makerspaces focus on scientific concepts and technological tools/techniques alone, students' making will remain limited to, and by, the known techno-scientific. Further, Makerspace activities that expect student making to end in a single iteration would block the imagination role of the prototype. Understanding and enabling a design process like the expanding spiral could allow for overcoming these constraints. Further research would be necessary to operationalize these suggestions into curricular modules, activity structures, and pedagogical scaffolds in makerspaces.

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