Emergent Investigations in Design Practice: Lessons from Engaging the Social Sciences Undergraduates in Design-based Concept Learning

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Abstract

This paper reports the findings from an engagementof social sciences undergraduates in design thinking, whichencouraged them to identifyrelevant conceptual ideas in life sciences that can be applied for societal welfare. About 12 groups of 4 to 6 undergraduates (participants)worked collaboratively on a design task around an idea identified and owned by the group itself. A case study approach enabled closefollow-upon the group's workby analysing their visual and written productions, and prototype outcomes. Evidence from two casesis used to exemplifydesign-based concept learning and understand how the experience of designing necessitated emergent investigations. The design thinking process afforded close attention to structure-function relationships, deepened an understanding of concepts, conscious understanding of material properties and assemblies, and building empathetic perspectives for appreciation of natural design and human-designed technologies. The emergent investigations undertaken by a group during the various phases of designing suggests its critical role in systematically evaluating formative design ideas, supporting iterative reflexivitythrough an interplay of materials, sketches and models that afforded conceptual transitions.

Keywords: *emergent investigations; design-based concept learning; scientific and technological literacy; STEAM education*

Background and Rationale

The need for building scientific and technological literacy (STL) through the curriculum echoes in education reforms across the globe (de Vries, 2012; Saracho&Spodek, 2008; Fourez, 1997). However, the meanings, thrusts, and educational valuesattributed to scientific or technological literacy demonstrate changing interpretations over time. For instance, an analysis of the past 20 years of literature by Valladares (2021) suggests a transition from a transmissive educational vision of scientific literacy that equipped learners with scientific concepts and processes for its application to a transformative vision that involvesa stronger engagement with social participation and emancipation. Similarly, Dakers (2014) noted a shift from an earlier emphasis on "being" technologically literate (denoting a telos or end-state),which encouraged critical awareness of the technological lifeworld to the renewed envisioning that articulates technological literacy as an ever-dynamic, on-going process of "becoming" literate within the changing technological world. Amidst this changed conceptual positioning,

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there has been a growing recognition for engaging with concepts and ideas beyond the orthodox disciplinary boundaries. On the global scene, this change reverberates in the Next Generation Science Standards (NGSS), which articulates the role of three distinct and equally important dimensions of learning: disciplinary core ideas, science and engineering practices, and cross-cutting concepts in the curriculum, enabling build a cohesive understanding of science over time (NGSS, 2013). On the Indian scene, a much greater emphasis on multi-disciplinarity approach has been promulgated in the recent National Education Policy (NEP) 2020. Overall, reimaginingeducational space holds the critical responsibility of engaging learners in conceptual content by providing knowledge through disciplines as well asafforading opportunities that facilitate meaningful connections of concepts, encourage modellingof ideas, and situate learning within authentic life experiences of learners. In seeking STL, the advice of Kirschner (2009)aboutmaintaining a distinction between the learning and doing of science is helpful. Often, the non-cognisance of this distinction results in the tension between epistemology and pedagogy. Among other ideas, the NEP 2020 emphasises the principles of synergy in curriculum across all levels of education, multi-disciplinarity, and holistic education (GoI, 2020). In such a context, the larger question concerns the kind of opportunities,which promote STL that can be carved within curricular spaces thatallow for productive learning engagement.

Several educationists (Saltmarsh, 2010; Kincaid & Pecorino, 2004) and pedagogues (Kumar, 2009; Pathak, 2018) have argued the need for engaging with research and experimentation to rejuvenate pedagogies and conceptual ideas. The educational experiences centredon *designing*have been known to establish empathetic connections between the content and learners (Surma-aho&Hölttä-Otto, 2022). Retracing the notion of design suggests two critical threads of impact on educational practice. Etymologically, design connotes a noun, verb, and adjective. This implies that design refers to both the process and outcomes involving the act of designing. As an adjective in design thinking, itdelineates from the other forms of thinking, highlighting the qualitatively salient and discursive learning experience rather than a mere categorical distinction. Conceptually, design has been argued, by its proponents, as representing a "third culture", distinct from the other two dominant cultures of arts or humanities and the sciences.

Table 1 summarises ideas identified by Cross (2006, 1982) to discern the nature of focus and process of engagement in the three cultures. While these distinctions may have helped in the past to characterise the nature of disciplinary orientations, in contemporary times, these serve to seek balanced appreciation of learning, especially in ensuring multi-disciplinarity exposures that enrich our practice. The extensive proliferation of *designerly* orientations in reimagining educational studies and practice is a case in point. Examples manifest in design-based research methodologies (Anderson & Shattuck, 2012), design experiments (Collins, 2010; Cobb, Confrey, diSessa, Lehrer & Schauble, 2003), and design-based learning (Kolodner, Camp, Crismond, Fasse, Gray, Holbrook, Puntambekar and Ryan, 2003) approach to learning. Scott, Wenderoth and Doherty (2020) assert that design-based research investigates the "learning ecologies" that move student thinking toward mastery. Given the transformations in the educational landscape, it becomes crucial to ask how can the educative experiences be orchestrated with design thinking so as to provide authentic, meaningful and enriching opportunities for learning about science and technology.

Table 1: Distinctive features of the "three cultures"(adopted from Cross, 2006).

Criteria	**The culture of**		
	Sciences	**Arts / Humanities**	**Design**
Phenomenon	The Natural World	Human experience	The Artificial World
Methods used	Controlled experiment, classification, analysis	Analogy, Metaphor, Criticism, Evaluation	Modelling, Pattern-formation, Synthesis
Values	Objectivity, Rationality, Neutrality, and concern for 'truth'	Subjectivity, Imagination, Commitment, and concern for 'justice'	Practicality, Ingenuity, Empathy, and concern for 'appropriateness'
Purpose of education	Transmission of knowledge about a phenomenon of study	Training in appropriate methods of enquiry	Initiation into the belief systems and values of the 'culture'

Theoretical and conceptual orientations

The study design and analysis have been informed by the socio-cultural tradition of Vygotsky (1978),which characterises human thinking and action as critical to learning. The mediational interactions *with* and *through* materials, tools, symbols, and social communication that support thinking and transform practical activity are dimensions of interest in this study. Further, the experiences of practical activity involving designing and making afford for a focus on the processes of learning. The analysis zoomed into moments involving collaborative engagement to understand learners' cognitive struggles to scope ill-structured problems through the use of materials, use of prior knowledge and imagination, influences that contoured reflective transformations of ideas, and fluid movements between cognitive and physical modelling of ideas. While an exhaustive discussion of all these ideas will be difficult to achieve in this paper, the effort is to capture transitions noticed during the process of design engagement and highlight the prospect of "emergent investigations" in enabling contextual motivation for pursuing the use of scientific concepts through design thinking. In this study, design thinking is envisaged as a mediated activity that affords empathetic, contextual navigation between the social and the individual.

The process of designing is acknowledged as a specialised kind of problem-solving, which deals with wicked or ill-structured problems (de Vries, 2020). Inquiry or investigations have been of critical interest to the learning of science. Based on the relative extent of autonomy to learners concerning the formulation of goal, question and procedure (method) pursued, Heather and Bell (2008) identify a four-level continuum to classify the levels of inquiry in an activity as confirmation, structured, guided and open inquiry. The student-generated questions of 'wonderment' (comprehension, prediction, anomaly detection, application and planning) kind, as opposed to those addressing 'basic information' or 'surface learning' approach, have been found to be productive in enabling science learning(Chin & Brown, 2002) and support open investigations(Chin &Kayalvizhi, 2002). Further, Chin (2002) underscores the critical agency of teachers in helping students to identify the worthwhile problems to investigate. However, studies in science education caution us to challenges associated, which arise from the open-ended investigations being perceived differently by the teachers (Dunlop, Diepen, Knox & Bennett, 2020) or from a mismatch between the intended and the student-experienced curriculum (Hume & Coll, 2010). Metz (2004) noted that learners' appreciating and addressing uncertainty in their own investigations is critical for effective scientific inquiry. The contexts of design problem-solving involve investigations that are not just open-ended but also ill-structured and engage with uncertainties, often both for the learners as well as teachers.In the context of technology education, Kimbell, Stables and Green (1996) consider investigation as an initial phase and refer it to "any activity which involves pupils in collecting information which is directly relevant to their task. This could be achieved from a wide range of sources, including books, CD-ROMs, experiments with processes, material tests, conversations with, demonstrations by, or questions to the teacher or any other 'expert'. It occurs at any point in a project." (p. 54). Although investigation can happen at any point, it seems to be conceived as a structured activity with the explicit intent of gathering and supplying information to the participants who have been given a design brief engaging them into design thinking.In such endeavours, the investigations are often pre-planned and scripted by the teachers. What are the contexts and kinds of investigations initiated and led by the participants? Studying the context in which investigation sets into motion and how it impacts design thinking is a line of interest that needs perseverant engagement. Further, investigations can reveal the internalised concepts and processes of engagementin learning, especially in contexts that demand connections across the disciplinary domains.

Design thinking can be related through features of design culture and *designerly ways of knowing* (Cross, 2006). *Designerly* thinking mediates curricular content and proffers imaginative transfer of understanding to the appropriated contexts identified as relevant by the learners, encouraging us to harness the confidence and interest of learners in STEAM (Science, Technology, Engineering, Arts and Mathematics) education (Kijia& Sun, 2021). Design as an iterative process of sustained thinking, consolidating and reflecting is also mediated through sketches and material explorations. The diverse role of sketching in enabling human cognition during the design process has been well established across all ages, from the early age (Hope, 2018) to professionals engaging in designing (Goldschmidt, 2017). Tracing the sketches allows track progression in ideas and provides a window into design cognition (Khunyakari, 2015). Acknowledging design as a fundamental human cognitive capability manifested through cognitive modelling (Roberts, Archer, & Baynes, 1992) favours a discursive role for design in learning. While Wells (2013) argues for the role of design thinking in building technological literacy, Kimbell & Stables (2007) assert the relevant need and salience of building the design capability with the curriculum. At a meta-level, a group of researchers identify close parallels between the ideas of design progression and the biological process of evolution (Ziman, 2000).While the instrumental mediation of design for accomplishing the curricular and pedagogical goals are often underscored, an elaborate understanding of design process engagement in diverse learning contexts is revealing. The study reported in this paper attempts to elaborate on both these aspects.

Barlex (2009) has argued that science can be used in teaching and learning design and technology education. This study attempts to present an alternate proposal wherein the design thinking process can support authentic and meaningful learning of the sciences. The study seeks to demonstrate that design and technology education experiences can be reliably used to drive learners' motivation into thinking scientifically and encourage learners to search and navigate knowledge ideas relevant to their immediate context of design. If structured carefully, the context may open prospects for deep learning, guided by an empathetic stance towards society. This viewpoint is consistent with the idea of design-based concept learning (DBCL) in science and technology education proposed by Ineke-Henze and de Vries (2021). Characterised as belonging to the family of social constructivist approaches to learning, the DBCL framework argues for convergence of concepts, design-based processes, and multi-disciplinarity in education. Further, the DBCL framework foregrounds the valued contribution of design experience in making abstract concepts tangible or operable, enriching knowledge through systematic iterations while designing and the crucial agency of teacherin supporting learning.

Research questions

The study investigated how an experience of design thinking, included within the teaching and learning of life-sciences course, impacted learners' thinking and reflective engagement. The study retraces learnings assimilated from the design experience and explores the dialectical interconnections between science and design process, mediated through emergent investigations. The study addressed the following research questions.

1. How does the process of design thinking manifest during the various points of collaborative engagement? What insights does it bring in developing an appreciation of the design process in pedagogic practice?
2. How are emergent investigations salient to the process of design thinking and science learning?

Operationalisation of critical constructs

Constructs, critical to the study, are operationalised by drawing upon relevant ideas from the literature and analytical observations gathered from the data.

Designerly ways of knowing

An engagement in design thinking has been known to involve five aspects that characterise *designerly ways of knowing*.These include tackling ill-defined problems, mode of problem-solving being solution-focused, mode of thinking being constructive, use of codes that translate abstract requirements into concrete objects and employing codes to read and write in object languages (Cross, 2006).

Emergent investigations

The features that characterise emergent investigations are based on when they occur during the design process, how they contribute to shaping ideas and the purposes they serve for the learners. Unlike predetermined, structured investigations leading to the next course of actions, emergent investigations arose at various points during the group's project engagement: while exploring design ideas, during sketching design ideas, while working with materials, while evaluatingartefact sub-componentsand assembly functioningand during the making. Observations or inferences from these investigations visibly impactedthe group's design ideas. In other words, the investigations shaped or transformed the group's earlier ideas. Theseinvestigations were self-directed and rendered to meet specific, immediate objectives, which contributed to clarifying, refining or evaluating ideas for going forward in the design-and-make project. Given these characteristics and their generative nature, these investigations have been collectively referred to as "emergent investigations". They represent conscious systematic efforts, closely follow principles of scientific methodology, and often result in nudging the disciplinary knowledge base of life sciences that hasbeen historically assimilated over the years.

Methodology

The research design used is a descriptive case study (Yin, 2003). Cases allow studying a phenomenon in its context, using evidence drawn from various data sources. Since the participants collaboratively engaged in design thinking, the problematisation of the goal, generation of design ideas towards potential solutions, and reflections were all co-produced by group members, creating a cohesive space for studying their cognitive engagement. Besides representing a cohesive collective guided by a sense of purpose and direction, the case as a unit of analysis allowed for systematic capturing of evidence for progression in design ideas and insights about contexts that afforded opportunities for expanding understanding of life sciences. At one level, the bounded nature of cases could be mapped directly with the theme that each group chose to work on. At another level, discussion about findings from cases afforded opportunities for reconciling some interesting insights from across cases that follow the same thematic area—for instance, insights from cases that studied prosthetics.

Study participants

The study participants included57 learners enrolled in the 5-year Integrated Bachelors of Arts in Social Sciences (BASS) programme at the university. The author, a teacher-researcher, developed and taught a core course on Introduction to Life Sciences. The participants were from across the country and represented diverse socio-cultural, disciplinary backgrounds (from the arts, commerce and science streams) and linguistic exposures. Usually, the social sciences undergraduates aim for a career in the social development sector and often come with disinterest in the sciences. Addressing the disinterest and seeking relevance between the sciences and the social sciences in the beginning year poses a challenge. The study reported was an integral part of course teaching and involved participants who volunteered to work in 12 groups, each groupconstituting4 to 6members. Individuals within each group were encouraged to work collaboratively towards identifying and developing design ideas that they considered addressed a social problem and required the use of knowledge of life sciences. Groups worked on projects spread over a month and a half in which they modelled their design ideas and, in the end, communicated their work to the entire class.

Context and process of design engagement

The life-sciences course aimed to develop an appreciation of fundamental ideas that have contributed to the advancement of human knowledge. Going beyond just explaining the concepts, the pedagogic effort was to help students locate ideas within their historical contexts, relate to the processes involved in the discovery of scientific insights, and develop an understanding of the nature of socio-cultural and political influences that shaped scientific endeavours. The course was organised around five critical questions: (1) how do we understand life, (2) what organisation makes life possible, (3) how does life lead to a new life, (4) what explains the diversity and connectedness among living beings, and (5) how can an understanding about life benefit thinking about society. In attending to these larger questions, the course discussed the salient ideas which transformed erstwhile knowledge and reformed human thinking and understanding. For instance, establishing the biological cell as the structural and functional basis of life, the role of biomolecules in complex functioning, processes in transmission of characters (Mendelian genetics), and change over generations (evolution). Through revisiting ideas, course participants were encouraged to find the relevance of ideas in contemporary contexts.

Thisstudy discusses the specific effort of encouraging learners to seek the relevance of lifesciences ideas for the present-day society.Each groupbrainstormed ideas thatthey thought necessitated knowledge of life sciences and contributed to society. The ideas brainstormed by all groups were listed on the blackboard. From these ideas, those found to be interesting, different (challenging), and practically doable (where laboratory or workshop will not be required, but visits to such spaceswere possible) were selected and confirmed by groups through class discussion.The intent and the manner in which the study has been conducted represents a case of what has been characterised as Design-based Concept Learning (DBCL). The analysis and insights drawn from the design-based projects are the focus of this paper.

Data: Sources, Processing and Analysis

Each groupwas requested to maintain a portfolio, which capturedthe process of design thinking leading to the development oftheirgroup's model artefact. In the portfolio, groups were encouraged to maintain minutes of their meetings, sketches and descriptions used during ideation, records of investigations undertaken, recordany empirical data gathered, and the outcome (model) produced from the project engagement. Some groups included reflections on the process they experienced.

Through a careful revisiting of records, the portfolios helped trace progression in the learners' thinking. Towards the end of the project, each grouppresentedto their peers, allowing critical appreciation and feedback opportunities. The processing of data led to developing case descriptions for each group and then identifying evidence for connections with life science ideas and the nature of shifts noted in thinking.

Analysis and findings

The analysis of engagement in design-based concept learning (DBCL) elicited three salient insights about learner engagement: (a) learners subscribed to *designerly* ways of thinking, (b) they used emergent investigations to support their *designerly* engagement, and (c) they creatively deployed scientific concepts and methodologyin design tasks.

Two exemplar cases present interpretative analysis involving 12 groups engaged in DBCL. To achieve a non-hierarchised representation of the salient insights, the reportingmaintainsa normative structure consisting of*case description*, manifestedevidence of *designerlythinking*, exemplars of *emergent investigations in design practice*, and a *reflective commentary*on each case. The brief yet comprehensive case description attempts to capture thedesign intentof members in the collaborating group, the process involved, and the outcome (model) from the engagement.

Case 1: Multipurpose footwear (for all occasions, all seasons)

Case description: A group consisting of four individuals collaborated towards developing ideas for comfortable, steady, and multipurpose footwear suitable for all occasions and seasons. The group initiated into design thinking by raising questions to reflect on why people prefer a brand, what considerations of materials and durability shape our choices, and the kind of preferences noticed among different age groups. The brainstorming led the group to explore details about the different materials and kinds of footwear available. It motivated them to dig deeper into aspects of history, culture, religious beliefs, and product usage patterns. The knowledge gained from different explorations enabled group members to reflect on technical considerations, preferences of potential users and provided a context to relate to the human need for appropriate footwear. The group explored the anatomy of human legs and feet. They anticipated that the bodyweightmight correlate with the user's desire for comfortable footwear. They planned an empirical investigation to identify whether user preference patterns could be linked with the structure of feet and the body mass index (BMI). They invested in understanding and discussing diseases associated with faulty footwear by the explorative reading of articles and consulting an orthopaedic. Figure 1 depicts different emergent investigations conducted by the group to understandappropriate footwear, which fed into their design ideas. The process culminated in detailed designs represented as drawings of the component parts and assembly structure. A crude attempt was made to model the layers and assembly through cardboard, thin foam, and other readily available materials (see Figure 2).

Designerly thinking: The design process elicited many exciting opportunities for engaging with concepts and the process

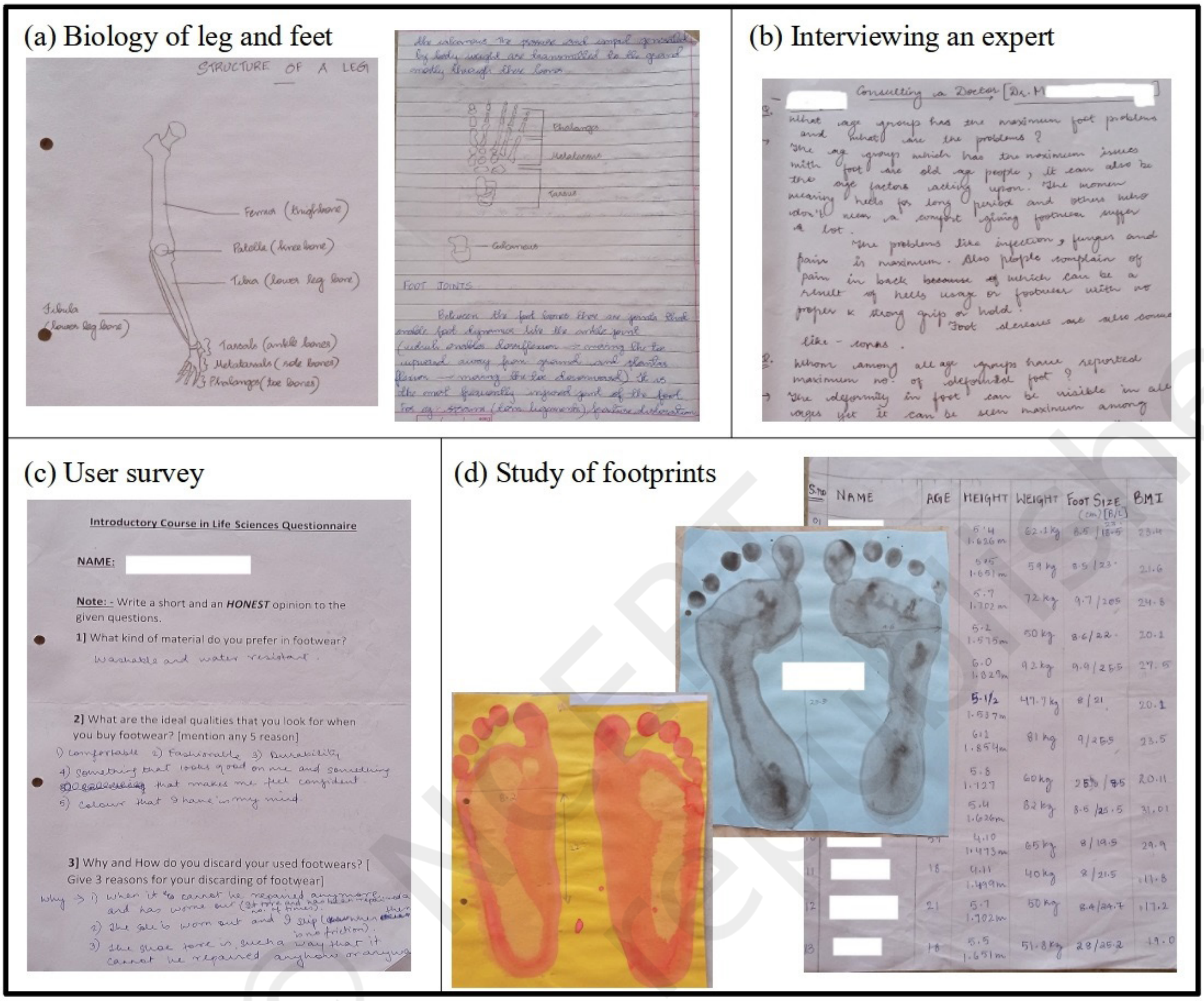


Figure 1: Modes of emergent investigations

of doing science. The historical investigation using books and internet resources about the advent of the human use of footwear led the participants to fascinating facts and features about footwear. For instance, the archaeological evidence of the first shoe in the middle palaeolithic period (about 40,000 years ago) helped them appreciate the connection between human livelihood activities and society's technological inventions. The participants were able to map changing materials and designs to the evolving periods of human civilisation;for instance, the prominence of foot injuries during the nomadic period to the demands posed through agricultural labour. The material diversity included footwear developed from cork, rubber, leather, wood, jute, cloth, plastic, etc. A map of diseases caused by inappropriate footwear during different periods (wherever records were easily accessible) was made. The group discussed the specific causes of conditions such as calluses, corns, hammer-toes, claw toes, etc.

The association of footwear in religious beliefs revealed a revered symbolism. The removal of footwear outside a temple, mosque, or home symbolises the sanctity of a place. Leaving footwear outside these

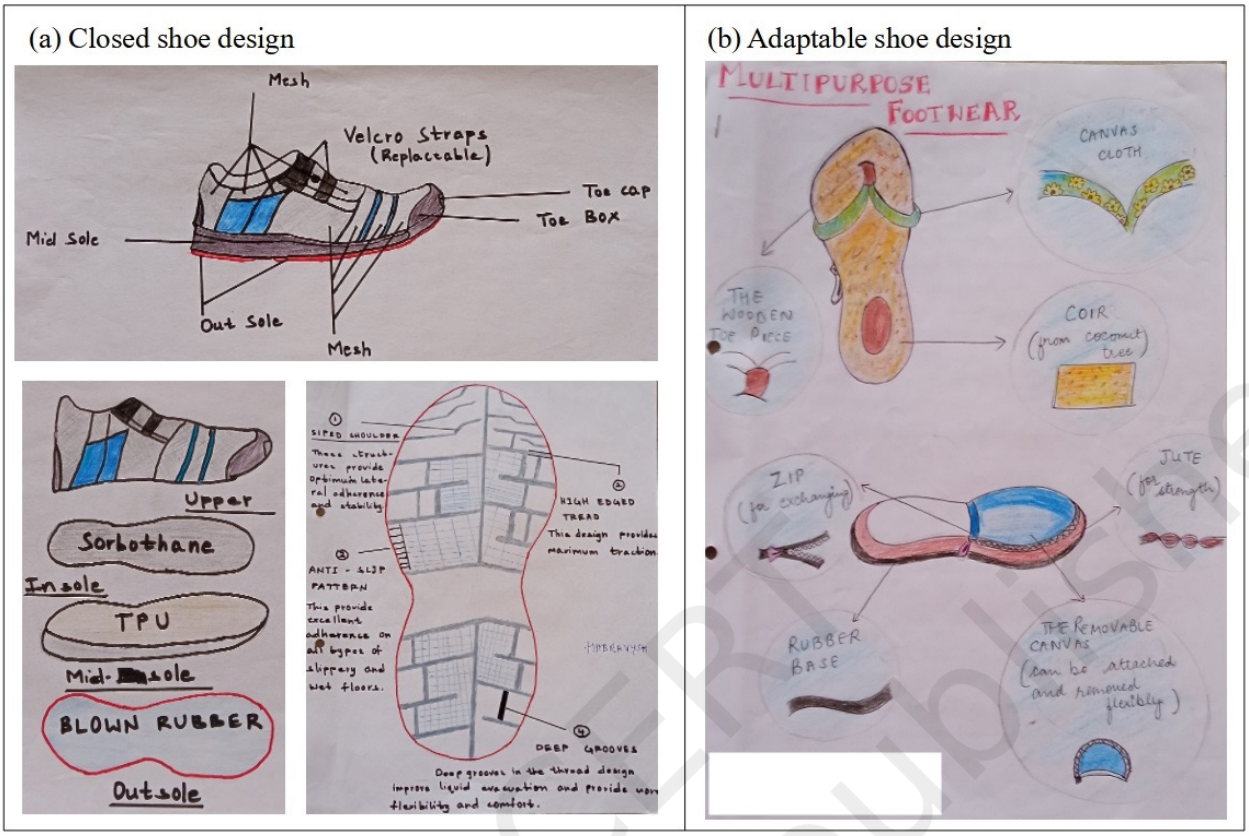


Figure 2: **Multipurpose footweardesigns**

spaces suggests a mark of respect and humility in Hindu and Muslim cultures. Ironically, on the other hand, footwear has been the object of social discrimination in a caste-ridden society (Ilaiah, 2007). *Dalits* or untouchables have been considered "impure or polluted" and are still prohibited from entering households of the upper caste wearing footwear. Linking to a caste-based understanding is to identify who makes footwear. Making footwear is traditionally looked down upon as a livelihood, practised by the *dalit* community of *Chamars* (footwear-makers or leather workers). The group reflected on how the industrial revolution or mass production has affected small-scale production of footwear and what it means for the footwear producers to become labourers in mass production factories.

Emergent investigations in design practice: The group investigated the morphology (length, arch, area, etc.) and anatomical details of the foot (bone, nerves, etc.) by referring to books on biology and footwear. In the process, the participants gathered appropriate vocabulary related to the natural architecture of feet, which they used later in their designs. Through references, they identified ways for suitably measuring and detailing feet structure, which includes the concept of sole dimensions, arch elevations, measuring depressions. They carried these constructs to their empirical investigation.

The interview with a doctor allowed the group to gain informational patterns like recognising that old-aged persons and women largely sought foot treatment for pain in feet, fungal infections or swelling in feet. The age group of 30 to 45 years reported deformities owing to inappropriate footwear, improper hygiene, or allergies to leather or synthetic materials. In this context, the group discovered the value of eco-friendly or natural materials, which they later on used in their designs.

Apart from gathering information about footwear from knowledge sources, the group undertook some empirical investigations. The group explored the relation between foot shape and structure with regard to age, body composition, and gender. Interestingly, footprint analysis revealed slight differences in the left and right feet. Typically, the average foot length of males was found to be larger than that of females, with a mean difference of 2.15cm. The role of BMI suggested that individuals with varying BMI scores had the same foot length. But, in general, a person with a BMI greater than 25 demonstrated a tendency to have flat feet, while those with BMI less than 18 showed slender feet with well prominent arch impressions. The relative quantities of adipose in persons with different BMI may be a plausible reason for this trend. The survey of individual preferences suggested that,

> *"Most of them …focussed on aesthetics, comfort, and durability. However, tall and overweight people preferred a larger size and strong base. They have problems in finding the right size footwear. As a result, our footwear will focus on all sizes."*

These investigations led participants to ascertain the criteria that they considered salient and incorporate these in their envisioned designs. Such an approach of using design opportunities for authentic use of diverse sources and perspectives to scaffold learning from real-life contexts and work towards inclusive designing is gaining increased attention (Rieger & Rolfe, 2021).

The idea of footwear for all occasions and all seasons was mooted in the early stages and persisted through the process. Such enduring ideas that get associated early on, sustain themselves and inform design have been referred to as "primary generator" (Darke, 1984). Findings from investigations also seemed to endure and contribute to design imagination. These tended to serve as "adjunct primary generators" (to borrow Darke's idea of a primary generator). Khunyakari (2019) noted that the underpinning of ideas to contextual values often strikes a chord with the participants engaged in designing.

Reflective commentary: Reflecting on this case, we notice a reflexive and iterative relation between participants' emergent investigations and their evolving design ideas. While the investigations addressed some specific goals, they seemed to serve a dual purpose in design thinking. At one level, they enabled to decipher the contextual salience and relevance of an idea to the larger goal. On another level, emergent investigations provide perspectives and evidential insights from different standpoints. This seemed to feed into alterations that the group explored during the course of designing and in their final ideas. For instance, the considerations of firmness, safety, and comfort guided the development of the closed shoe model (Figure 2a). In contrast, flexibility, eco-friendliness and comfort guided the notion of an adaptable shoe design (Figure 2b). Avenues to the self-motivated pursuit of knowledge and process of science manifested in conducting emergent investigations, adopting vocabulary, choosing materials, weighing alternatives, considering assembly and structural reinforcements.

Case 2: Biomimicry and ioinspiration – The robotic hand

Case description: A group of six individuals collaboratively brainstormed to work on an idea close to the life-form functioning. They thought of exploring biomimicry in tools and toys, but they wanted to cover different age groups. Group members decided to visit the local market to identify the kind of everyday stuff that is either inspired by nature or mimics it (for example, jewellery, toys, etc.). They arrived at the idea of designing an instrument that helps pick everyday objects (scissors, paper, string, straws, etc.) and places it elsewhere. Eventually, they realised that developing a robotic hand is what they would like to design and construct. The group's designmetamorphosed at various points, taking into account ideas and insights from the emergent investigations conducted. The evolution in design does not merely reflect a change in design ideas but also demonstrates changes of reconsideredmaterials, crafting, assembling, and even desirable functionality.

Designerly thinking: It is interesting to notice how the journey from designing an instrument to pick artefacts to the robotic hand was governed by self-motivated investigations, which enabled the participants to scope and eventually bring greater orientation to an ill-defined problem. The solution or goal of achieving basic vertical and horizontal movements seemed to steer their design decisions. These included the choice of materials, changes in structure, expanding or even refining design ideas for achieving coordinated control of digits. Interestingly, both thoughtand material transformations were supported through sketches, models and investigations with concrete materials. Ideation through sketching brought out the language use of design and technology and contoured the group's imagination of evolving design ideas (Figure 4). Tracing the progression in the group's design ideas suggest some critical transitions. These include moving from the use of the principle of suction to a digitate mechanism in early design, a shift from a 4-digitate contraption to a 5-digitate structure that conceptually parallels human hand, moving from the cylindrical pipe as a suitable structure for fingers to a flat, cardboard structure with a textured finish for grip, and the struggle to use strings instead of wires organised like muscles to achieve co-ordinated movement of digits. These design decisions represent an internalisation of material solutions that offer pragmatically feasible affordances for meeting design needs.

*Emergent investigations in design practice:*In the initial stages of the design process, group members proposed ideas with a semblance to the morphological structure of hand: funnel for palm structure, pipes for fingers. They were intrigued about the basic functions that their robotic handscould do. The group decided to study the hand structure, and they started documenting routine functions of the hand, such as grasping a bottle, opening the lid, holding a pencil, etc. Through the encounters of various objects, they realised the role of a broad palm that provides support and works in conjunction with fingers for achieving *horizontal functions* like holding a bottle, pushing things, etc. In contrast, the fingers work together for attaining*vertical functions* like turning the lid, lifting, pulling, etc. (see Figure 3a). They were able to deduce the critical structure and positioning of the thumb in relation to other fingers (note the dotted line connecting the tip of the thumb with parts of digits and visually represented deduction about the "main moving part" in Figure. 3b).The group's empirically derived understanding of the structure and functioning of the human hand closely resonates with Purcell's analytical retracing of humankind's technological progress to the biological benefits afforded by the unique structure of mammalian hand.

> *"...mammals whose hands and feet have fingers and toes ending in nails rather than claws. Not only that, but the tip of the thumb can touch the tips of the other four fingers.*
>
> *These "prehensile" – that is, grasping – hands with their "opposable" fingertip-touching thumbs are one major benefit that (hu)man enjoys because (s)he is a primate." (Purcell, 1982, p.4)*

The group developed two design variants: (i) a complex, hemispherical model with strategically placed digits and (ii) a cardboard base with four finger-like projections held together by a rubber band and operated by strings. The evolution from (i) to (ii) is evident through a change in materials, refinementsto accommodate the need for serving to hold and pick things. The larger purpose of the model was to emulate the hand structure and functioningto achieve some fundamental movements.

The emergent investigations anchored initial ideas and supported developing a

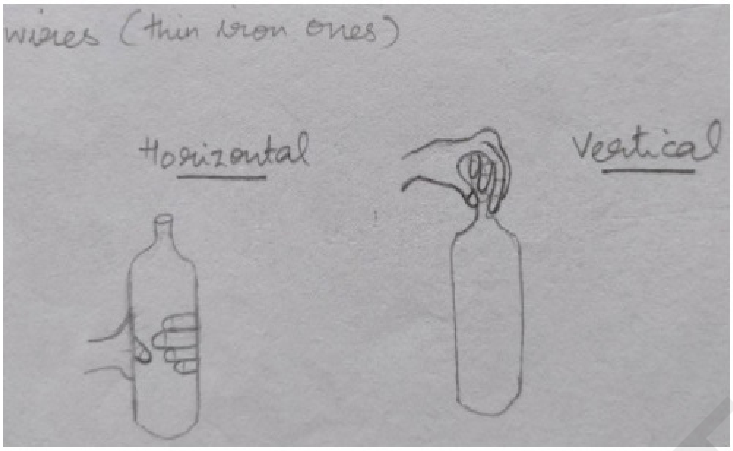
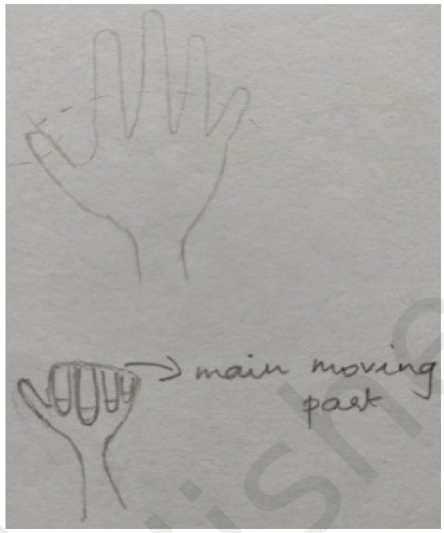
(a) Uses of "prehensile" hand (palm & fingers)	(b) Relation of thumb & fingers
	

Figure 3: **Explorative investigations of hand structure and functioning**

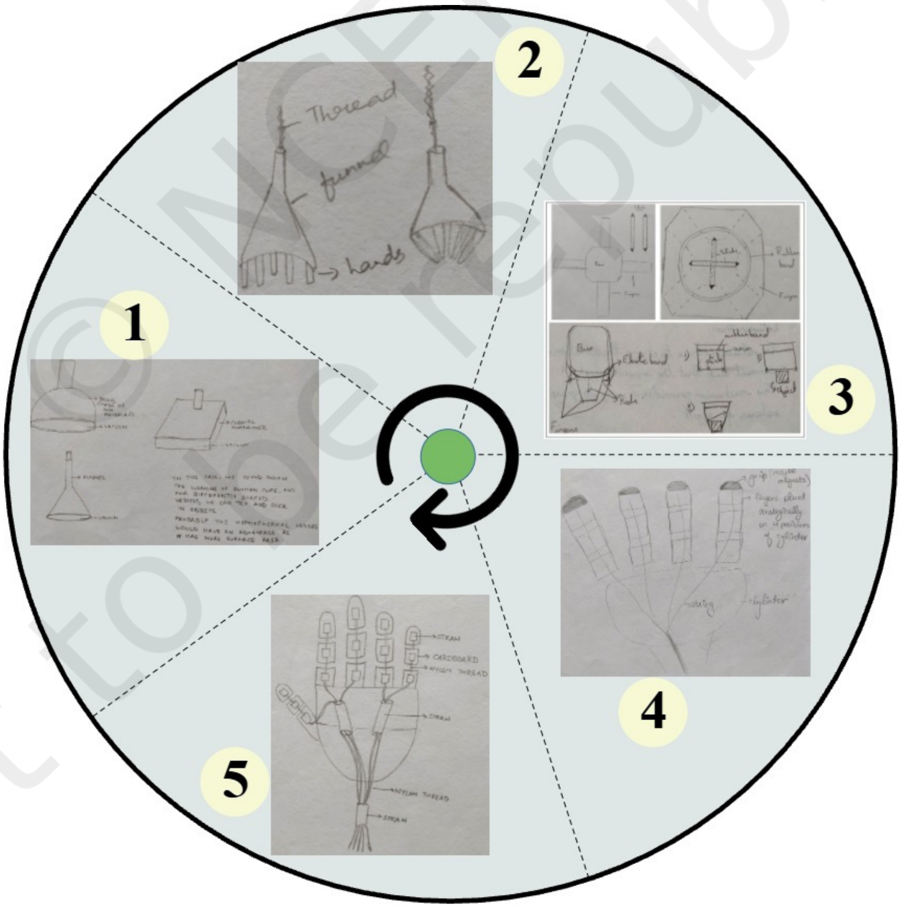


Figure 4: **Evolving ideas of the robotic hand**

refined understanding of specific aspects that inform the group's design ideas. For instance, the group identified bare essential movement as horizontal and vertical following a systematic exploration of materials in the immediate vicinity. The ideasdrawn from these investigations sustained and significantly shaped their design decisions. Further, the investigations initiated by participants contributed to scoping the range of associated ideas, thereby opening up newer possibilities (mechanical controls of varied kinds – electromagnetic, mechanical wires or strings) and enabling focus and attending to the details (from rods to pipes and jointed parts for a finger to achieve flexible control). The idea of closely studying the human hand as part of explorative investigation allowed the group to not just scope a range of possible functions for their robotic arm but also anchored the basic idea of digitate hand, which endured and even got refined through subsequent, iterative changes while designing. Two things can be deduced from the retracing. One, the initial idea of the digitate hand sustained itself over time and served as the "primary generator" in their thinking process. The idea endured even though it got refined, restructured or transformed radically. Second, the grounding of initial ideas gained anchor through self-directed investigations like sifting through examples that mimic natural forms, exploring a range of hand movements, closely detailing structure and functioning of the human hand, etc. One such exploration led the group to see stretched palm and map a relation between the structure of thumb and other digits (see Figure 3b), appreciate the 3-component structure of each digit and its contribution tothe functioning of the hand (refer to Figure 4). This understanding was incorporated by making the digits of the robotic arm flexible.

The desire to achieve coordinated movement was realised through a later shift to cardboard model and using strings to organise the arrangement of the digitate robotic hand. Interestingly, through the process, the role of muscular structure in hand seemed to shape the organisational detailing of string arrangement. In the overall process of emulating the human hand to create a robotic hand, the role of analogical mapping manifested seemed to go beyond mapping the surface details of the base analogue (artefact serving the motivation) (Gentner&Maravilla, 2018). Instead, the emergent investigations established deeper, conceptual connections between the structure-function of the human hand and the modelled structure (Stevens, Kopina, Mulder & de Vries, 2020). The evolution in design ideas bears a testament to this fact.

Reflective commentary: The retracing of design ideas suggests that the design idea has been in flux and was getting refined by considerations arising from investigations, materials, and even practical purposes. The struggle with the evolving course of ideas suggests an almost invincible drive of the participants to convert their design ideas into practically realisable existence. While the design of the robotic hand could well have served the intentions of prosthetics, the design development was induced and followed copiously as a case of bioinspiration, suggesting that motivation and intentionality of designers has a *prima facie* role in developing design thinking for learning. This point becomes evident in another case, where the contrast manifests in how the group engaged in design thinking. Another group pursued investigations on prosthetics by surveying ideas about prosthetics. Their enquiry led them to empirically establish that most respondents did not consider artificial eyes or spectacles as prosthetics. The group decided to deepen their understanding further, as revealed in their reflections.

> *"As the days progressed, we delved deeper into the field of prosthetics, implants and silicones. We discovered how little awareness we people have about such an expanding field and an important one...Even implants and spectacles come under the purview of prosthetics." [Case 3: Team Pro(sthetics)]*

Engagements in such authentic learning experiences based around ideas of diversity and inclusion can help develop a sense of belonging and positive STEM identities (Singer, Montgomery &Schmoll, 2020).

Discussion

This study is about how an experience of design thinking, included within the teaching and learning of life-sciences course, impacted learners' thinking and reflective engagement. We draw upon the analysis of the two cases reported and extended them with empirical generalisations from analysis of other cases in an effort to consolidate some shared insights. From a synthesis of cases, one can reasonably deduce that the design and technology education experience was used by social science undergraduates to think of diverse design problems through which they connected their knowledge of life science to society. Although their themes were different, each of the 12 groups did engage in some act of designing and making an artefact of relevance for society. The participants' wide range of topical areas required different levels of attention and engagement. Some projects were information-oriented, and design was guided towards means to developing sensitisation on topics like psychoactive drugs, abortion, biotechnology and its applications, social behaviour of dolphins, and breast cancer. Other projects probed existing alternatives and developed prototypes such as the topics on biomimicry & bioinspiration (robotic hand), waste management, vermicomposting and camouflage. Still, other projects demanded creative experimentation and data-based designing, such as topics on prosthetics, multipurpose footwear, and narcotics. Invariably, the cases seemed to be guided by an empathetic stance towards society.Further, the cases seem to exemplify substantive engagement with the concepts in science and technology; involve design-based processes of iterative reflection with ideas and materials; and engaged with knowledge and skills appropriated from multiple disciplines. Such a convergence makes these educative experiences examples of design-based concept learning. The teacher's involvement in learning discourse demanded versatility in facilitation depending on the demands posed by different cases, a salient characteristic of the DBCL approach.

For the participants, the necessity of an alternate, artefact imagination pushed them not just to foresee ambitious connections but also to deal with challenges in taking their ideas to a pragmatic solution. The process of collaborative thinking has a reciprocal impact on participants within a group, often creating opportunities for supportive contributions by individual members towards meeting a common goal, direction and mutually sharing the sense of purpose. Across the groups, collaborative interactions seemed to have an emotive, inspirational impact. A closer analysis of the two cases following the characteristics of *designerly ways of knowing* suggests interesting variations that manifested and are consolidated in Table 2.

Table 2: Designerly knowing evidenced in the two cases.

Elements of designerly knowing	Case 1	Case 2
Tackling ill-defined problems	Multipurpose footwear for all occasions and seasons translated into comfortable, sturdy and lasting footwear or as customisable by altering component parts.	The robotic hand as an expression of biomimicry and bioinspiration, not as a prosthetic.

Solution-focused mode of problem-solving	Constraints (eco-friendly materials, alterable parts) and considerations (stability, comfort, etc.) imposed through investigations.	Regulated and controlled movement of the parts of the artificial hand.
Constructive mode of thinking	Anatomy of human feet, consulting a doctor (experience of an expert), survey to gain user needs, empirical study to correlate BMI and shoe needs.	Mechanical, regulated digitate structure arrived by exploring-functions of the human hand.
Codes to translate abstract requirements into concrete objects	Sketching, interviewing experts, conducting surveys, collecting data using tools, feet impressions and measures.	Sketching, extending analogies (funnel, suction cup, etc.), and using mechanical principles.
Codes to read & write in object languages	Feet impressions, knowing anatomical details, re-fashion or alterable designs, considerations translated in choice of materials.	Regulatory movements of artificial hand-digits explored through different mechanisms; models used to figure out structures & functioning.

Across all cases, the transitioning from seed idea to progressive alternatives during the various phases suggested a process of appropriation and iterative refinement, mediated through sketches, choices in material resources, and guided by findings from emergent investigations. The prior knowledge and imagination seemed to get tailored through the emergent investigations, encouraging a fluid movement between the cognitive and physical modelling of ideas. Cognitive modelling through non-verbal (sketches and gestures) communication allowed scope for creative tinkering with conceptual ideas, mechanisms and assemblies. At the same time, exploring materials and allied artefacts allowed opportunities to validate and test ideas. For instance, cylindrical pipes and flat metal plates for fingers of the robotic arm were modified to jointed fingers and reinforced cardboard structure in the final design to achieve grip and flexibility. The exploration of scientific ideas and principles seemed to have been integrated with their emergent investigations. In this sense, the emergent investigations became salient to the process of design thinking as well as extendingtheir knowledge and skills from learning science. The social investment and time varied for the emergent investigations across groups. Some investigations required continuous and focussed investment of group members (for example, social survey on perception of prosthetics), others required continual follow-up after regular periods of time (for example, standardisation of medium for vermicomposting). The discussions around observations from emergent investigations were intense, demanding and salient in reshaping the group's design outcomes of product or process formulations.

Conclusions and implications

This paper reports a teaching-learning experience that centred design thinking as a means to providing authentic and meaningful opportunities for engaging participants with ideas in life sciences that can be extended to society. In the process, the participants drew upon concepts from science and technology and used them effectively to shape their design ideas. It was illuminating to note that the participants resorted to “emergent investigations” that were not pre-planned or occurred at a particular phase in their project. These were not directed to merely satisfy their immediate curiosity. The contexts and kinds of these participant-initiated investigations suggest the salience of these emergent investigations of being carefully organised to meet specific aspects of their evolving design thought. Interestingly, it related to developing an understanding of a *physical* (what affordances are possible in a particular arrangement of robotic hand?), *natural* (does BMI correlate with feet structure?) or *social* (what artefactual extensions of the human body get perceived as prosthetics?) phenomenon under consideration. Conducting these investigations called into play knowledge and skills of doing science, although they were not prepared to systematise their investigations and feed into iterative reflexivity in their design ideas. The findings suggest the need to pay closer attention to participant-led investigations rather than just considering it as one of the beginning phases of the instructional plan to get the participants kick-started into design-and-make engagements. The analysis of cases as examples of design-based concept learning (DBCL) engagements elicited three salient insights about learner engagement: (a) learners subscribed to *designerly* ways of thinking, (b) they used emergent investigations to support their design thinking, and (c) they creatively deployed scientific concepts and methodology in design-based concept learningengagements.

In conceptualising and attending to the larger idea of connecting life science concepts for societal welfare, the participants brainstormed on topical areas. As they advanced towards developing and refining their ideas, they started using *designerly* ways of knowing. The cases elaborated substantiate the evidence for such an engagement. Analysis suggests that during design thinking, the participants chose to conduct systematic, specific goal-oriented investigations that had a profound, lasting impact on design decisions. Ideas from emergent investigations that persisted and informed design decisions are described as adjunct primary generators. The transitions in design thinking illustrate how empathetic perspectives got internalised through the emergent investigations. For instance, detachable component parts became a unique aspect of the multipurpose footwear design. The emergent investigations were not premeditated but served as tools for navigating the contexts, concerns of purpose, and operationalising need in relation to the end-users – a rather muddy space of ideas. It seemed that the emergent investigations brought iterative reflexivity to design ideas, whereas thinking with materials, sketches and models afforded conceptual transitions enabling design ideas to fructify.

The retracing of progression in ideas and how participants related to design ideas demonstrated dialectical interconnectedness between sciences and the design process. Layton (1993) argued that articulating science with practical action would help project a more authentic view of the nature and creative foundations of scientific knowledge, thereby humanising the subject. Interestingly, the Indian social scientist, Ilaiah (2007) argued that the technical work of skilled artisans, craftspersons and labourers embodied an internalised scheme of practices that we tend to put together as science. The very motive of science can be realised through a serious acknowledgement and celebration of such practices in the curriculum and encouraging questioning about entrenched inequities in society. Analysing design engagement and emergent investigations hold the prospect of developing insights about how the growth of critical ideas in sciences and technology can be incorporated and supported through design-and-make exposures, especially in the higher education spaces related to the social sciences. Integrating design thinking with science learning offers the possibility of dissolving the three silo cultures and questioning the perceived identity of education as a "soft discipline" (Sarangapani, 2011) to move into a more eclectic and transformative space for deepening connected understanding.

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