Designing a Learning Environment to Nurture Tinkering in Engineering Design

A Thesis submitted in the partial fulfillment of

the Requirement of the Degree of

Doctor of Philosophy

by

Ashutosh Raina
164380001

under the guidance of

Prof. Sridhar Iyer

and

Prof. Sahana Murthy

IDP in Educational Technology
Indian Institute of Technology, Bombay

Feb, 2023

Dedicated to

every *kid-at-heart* who foster curiosity and externalise imagination by breaking and/or making *their toys*

Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

Ashutosh Raina

Signature

Ashutosh Raina
(Name of the student)

164380001
(Roll Number)

06 / 06 / 2023

Approval Sheet

This thesis entitled "*Designing a Learning Environment to Nurture Tinkering in Engineering Design*" by Ashutosh Raina is approved for the degree of Doctor of Philosophy.

Examiners

1. Samit Bhattacharya

Digital Signature
Battula K Chakravarthy (i01111)
08-Jun-23 08:47:04 AM

2. ______________________

Supervisors

1. ______________________

2. ______________________

Chairman

____

Date: 6 / 6 / 2023

Place: IIT Bombay, Mumbai

Abstract

There are several ways to solve engineering design problems. Among known methods, researchers have argued for tinkering as one of the authentic practices for solving engineering design problems (Berland, 2016). Researchers have also emphasised the value of multiple ways of knowing and learning, what they refer to as "epistemological pluralism", as some ways are authentic to some students (Turkle & Papert, 1990). Tinkering is one such helpful tool in one's problem-solving toolbelt. For some, it might be their primary tool and for others, a tool for specific circumstances.

Tinkering has been used in some contexts, such as hackathons for developing new solutions or design thinking workshops. Tinkering is typically emergent or incidental in such contexts if the right combinations of people and the environment come together. The focus in such scenarios has been on developing or learning new technologies or processes (Hielscher & Smith, 2014) rather than tinkering itself. In addition, a plethora of tinkering kits have emerged along with instruction manuals and pre-defined models, but they lack open-ended problems and scaffolds to support learners. Instead, these kits depend on the excitement towards using new technology and assume problem-solving behaviours like tinkering will emerge as the learners keep engaging or playing with the kits. The manual and model-based approach does not trigger or question the ability of what can be done with the components, limiting them to build the specified models. There is merit in designing a learning environment to nurture tinkering as a problem-solving strategy for engineering design problems, which is our research objective.

In this research, we use design-based research (DBR) as a methodology which allows us to address dual goals simultaneously: one through designing and refining a learning environment and the second by coming up with a theoretical understanding of how learners tinker (Puntambekar, 2018). Within the DBR iterations, we used the conjecture mapping approach, which helped us map the features of our learning environment to the learning processes they mediate and how they come together to produce a desired outcome (Sandoval, 2014). In the first iteration, we focused on exploring tinkering and how it can be used for problem-solving. Then we identified factors influencing the tinkering processes. We designed a pedagogy Xpresev (to be read as expressive) that operationalises tinkering for problem-solving in engineering design. We used Xpresev as the basis of our learning environment named "Tinkery 1.0" (an adaptation of the idea of a nursery that nurtures plants by providing them with a conducive environment to grow), designed in the context of solving problems in robotics. The components of Tinkery 1.0 are an ordered set of open-ended problems with multiple possible solutions, the resources, which in our context are the Lego Mindstorms kit, many scaffolds and the various roles a mentor assumes. The Xpresev pedagogy orchestrates the activities in the learning environment.

Further, in the first cycle, we conducted a study with Tinkery 1.0 and analysed our study data through interactions between the participants and the various components of Tinkery 1.0. Analysis of these interactions provided evidence of the design conjectures and helped us discover emergent challenges. The second DBR iteration focused on understanding and addressing the challenges by revising the learning environment, which led to Tinkery 2.0. In the second cycle, we conducted another study with Tinkery 2.0 in which the data analysis focused on interactions and actions performed by the participants when solving problems. This analysis provides evidence to support the modified design and theoretical conjectures. Evidence for the conjectures suggests that Tinkery nurtures tinkering in learners when solving engineering design problems.

This research contributes to the existing knowledge of the design and development of learning environments, specifically in activity design, scaffolding, pedagogy and the role of a mentor for nurturing thinking to solve problems in engineering design. These contributions support learners' agency for tinkering to happen. Regarding tinkering as an individual activity, there need to be more recommendations on the pedagogy and role of the mentor. Hence this research also fills that gap, contributing to the design and use of tinkering kits. We also discuss the importance of making one's idea tangible as an aid to performing epistemic action to uncover challenges which reduce complexity.

Further, through the manipulation of these tangible ideas, learners perform pragmatic actions to achieve the goal of solving the problems. Research in collaborative environments on making and tinkering can use these to analyse the dialogue between participants and the actions that follow as they share physical representations of ideas. These contributions have implications for researchers working with tinkering from the point of view of learning science, maker space, creative problem solving and engineering education under the broad umbrella of educational technology.

Keywords: Tinkering, Problem Solving, Engineering Design, Tinkery, Xpreseve, Learning Environment, Design Based research.

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Abbreviation and Glossary of Terms

AIM	Atal innovation mission (AIM)
ATL	Atal Tinker Labs
Bot	Robot
DBR	Design Based Research
DC	Design Conjecture
ED	Engineering Design
IR	Infrared
LE	Learning Environment
Lego Mindstorm EV3	Lego's Robotics controller brick
Lower Bound Sample	A sample on the lower boundary of the spectrum of the participants we have designed our solution for
MOOC	Massive Open Online Courses
PM	Partial Manpluable
RGB	Red Green Blue
STEAM	Science, Technology, Engineering, Arts and Math
Tangible Actions	Physical actions performed over tangible ideas (physical artefacts)
Tangible Ideas	Ideas that have been built using physical resources in a physical space.
TC	Theoretical Conjecture
US	Ultrasonic

Digital Version of the Thesis

We have made an attempt to create a digital version of this thesis as a website. The objective of the digital version is to present this research through different modalities of communicating ideas and sharing updated progress of this research work beyond what has been reported in this thesis. The digital version can be accessed on the following link or by scanning the QR code.

Link: https://sites.google.com/view/tinker-ed/home

Note: This attempt is a first of its kind to make a multimedia based thesis as per our knowledge and we will tinker with it so it's a work in continuous progress. At times if the site is not available please be assured it will be available soon with more exciting stuff.

Thank you for your consideration. :)

Chapter 1

Introduction

"Lead the child to construct for himself the tools that will transform him from the inside—that is, in a real sense, and not just on the surface."

- *Jean Piaget* in *To Understand Is to Invent*

This research aims to build a learning environment for nurturing tinkering in the context of problem-solving in engineering design. One could ask why nurturing tinkering when there already exist a number of ways for problem-solving in engineering design. In addition, a few other questions arise: what is tinkering? Why should we bother about nurturing tinkering? In the next section, we will focus on answering the questions mentioned above, build a background, and discuss the motivation to begin this research.

1.1 Background and Motivation

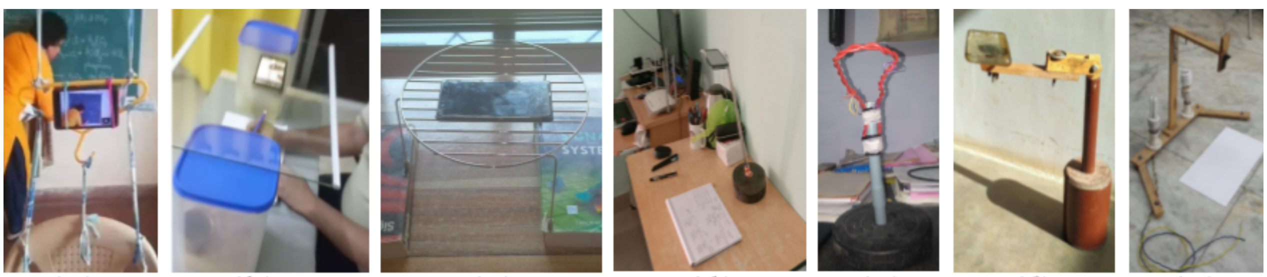
There are a number of ways to solve engineering design problems numerically and analytically through various methods like strategic design, human-centred design, design thinking etc. Among these known methods, researchers have also argued for tinkering as another authentic practice for solving engineering design problems (Berland, 2016). Researchers have also emphasised the value of multiple ways of knowing and learning, what they refer to as "epistemological pluralism", as some ways are authentic to some students (Turkle & Papert, 1990). Hence tinkering is one of the valuable tools in one's problem-solving toolbelt. For some, it might be their primary tool, and others a tool for certain occasions.

Tinkering from an observer's perspective involves a lot of iterations, which are exploration and play. When an iteration is observed closely, we see a process of finding a solution possibility (exploration) and making ways to get there (play). Such iterations of exploration and play performed in quick succession while addressing challenges that emerge lead to an important aspect of tinkering: the evolution of the solution. Tinkerers know how to improvise, adapt, and iterate, so they will not likely fixate on previous designs as new situations arise. They start small, try out simple ideas, react to what happens, adjust, and refine their plans (Resnick & Robinson, 2017). Based on this very nature of tinkering, researchers suggest tinkering as an approach that could simplify the complexity (Berland, 2016) of solving ill-structured problems and encourage creative processes (Resnick, 2007). Another varied understanding of tinkering is that of a mindset with which one approaches the problem-solving process. E.g. researchers have talked about closing the design thinking process with a tinkering mindset (Parisi et al., 2017). Tinkering can be a self-driven medium to nurture young learners' decision-making and design-thinking processes, where decisions are made based on gathering knowledge about problems while situated in the problem setting and optimal use of resources to meet an objective. Tinkering is one approach that provides learners with agency and an inductive perspective on the problem and solution rather than just a deductive perspective of a solution strategy. Yet we do not see tinkering being formally introduced on a large scale, especially in engineering design, or in some cases even encouraged in labs based on problem-solving (Atman & Bursic, 1996).

Tinkering is quite common in our everyday professional and personal lives though it is not visible as a formal practice. In India, its crude version, commonly referred to as "jugaad", does imbibe the essence of tinkering but, as we will see later, is just an initial step for tinkering. Tinkering tends to naturally occur under constrained circumstances where constraints may be in the form of resources, rules, economics or exposure, or they could even be self-imposed, like being cautious about how one uses specific resources. Researchers have discussed it as an informal practice in engineering design labs (Sekhsaria, 2018) and many national-level organisations like ISRO and Amul and missions like Aadhar (Jain, 2022). Tinkering has been associated with scientific discovery (Lamers et al., 2013). Tinkering has also been acknowledged in practices of medical sciences (Knowles, 1987; Mol et al., 2015), art (Lewis & Thurman, 2019), and domains of humanities (Wargo, 2018).

Let's take an example we saw during the movement of education on online platforms during the pandemic of COVID-19. In this move to the online medium, there was a need for a shared documentation medium like the board to explain while in a video conference or recording a video. Some tools allowed digital whiteboards but required laptops, tablets or hardware like a stylus not commonly accessible given their availability and cost. Initially, we saw many people trying elaborate contraptions to mount/hang/place phones to show the writing surface. Some are as seen in Fig.1.1 (a), where the affordance of a cloth hanger (suspension and retention) has been used to suspend a phone, mounting it on the hanger by tying it with a cloth / elastic material. A chair is tied at the bottom to keep the entire structure stable.

Similarly, in Fig.1.1 (b), we see a refrigerator tray, which is transparent and solid to hold a phone, is kept on top of two boxes with the phone on the top and the writing material below the tray. The boxes ensure enough space for hands and paper. These solutions are frugal and seem innovative initially, but if required to use consistently, they become tedious with the risk of the phone/tray falling and getting damaged. The person has to sit in a very uncomfortable position with the tray.



(a) (b) (c) (d) (e) (f) (g)

Figure 1.1: Contraptions and solutions for recording lectures in the early days of lockdown

People inspired by such solutions worked on overcoming the emergent problems building their solutions as seen in 1.1(c), where a grill tray is used instead of a glass sheet. Some who had a selfie stick mounted it on a base, as seen in Fig.1.1 (d) or as seen in Fig.1.1(e), a plastic pipe is used as a support mounted on a set of weight disks with wound copper wire strong enough to sustain the weight. These designs are still crude but better in usability with limited functional features like height adjustability. As resources became available, further refinements happened with self-built stands, as seen in Fig. 1.1 (f & g). These have evolved, addressing the challenges of flexibility, usability and stability. Now if you had to do a recording just for once, the glass stand would have worked, but if you have to do it a couple of times or had to be used regularly, then later designs would be more practical and reliable. So, the difference between tinkering from other approaches is in iteratively solving a problem by building solutions quickly and getting to know how they can be improved. Different ways are authentic for building solutions which work differently for different types of problems and preferences of the people, and tinkering is one such way.

The tinkering/making movement has gained tremendous momentum in the past decade. Maker faires started in 2006 and have become a worldwide phenomenon (*Maker Fair*, 2013). The upsurge of maker spaces has been part of the maker movement expansion, undoubtedly helping to fuel it. One of the significant indicators in this regard was the establishment of Atal Tinker labs by The NITI Aayog Govt. Of India under the Atal innovation mission (AIM) of 2016. Under AIM 5441, schools have established Atal Tikerlabs (*ATL*, 2019). Though there are changes at the school level yet the exposure to problem-solving, especially in the laboratories of first-year engineering students, is very systematic and by the book, which does not encourage exploration, curiosity building, and the need for investigation and discovery (Atman & Bursic, 1996). This lack of exposure hinders the opportunities for creative and innovative thinking.

We see a lot of researchers and practitioners from education, research and especially industry talk about "Jugaad (Frugal) ways of doing things", equating it to creativity, innovations etc. (Bhatti, 2013; Prabhu et al., 2013). In this research, we see Jugaad as a quick fix or a strong start towards solving a problem, but it might not work as a long-term solution. Tinkering itself as a buzzword is mentioned in hackathons for developing new solutions. The focus of hackathons is achieving a result or creating a product. Here the focus is on the result, and tinkering may be emergent (Happonen et al., 2020). Workshops discuss tinkering when imparting skills or technological processes to a young audience. Most of their curriculum is designed on design thinking principles, whereas tinkering may be emergent or incidental if the right combinations of people and the environment come together. The focus has always been on developing or learning new technologies or processes (Hielscher & Smith, 2014) and not tinkering.

A plethora of engineering design kits that claim to subscribe to tinkering have emerged, but not all of them ensure the freedom to tinker. A few kits, like the Lego mind storms, have been built based on tinkering ability and support tinkering by design (Jung & Won, 2018; Ruzzenente et al., 2012), but others are restrictive regarding usability. Most are just components put together with instruction manuals replicating different projects available online. Instruction manuals are a primary part of most tinkering kits but are limited to step-by-step instructions for given designs or models. They lack means for reflection, like basic worksheets on strategies to build shared models or how different resources have specific functions. Most of the kits come with predefined models and lack open-ended problems. The pedagogy claimed to be used by these kits has been defined as the pedagogy of play. As researchers point out, there is a need for certain scaffolds to ensure play happens even when the resources support play (Honey & Kanter, 2013). Instead, these kits depend on the excitement towards using new technology (novelty) and assume problem-solving behaviours like tinkering will emerge as the learners keep engaging or playing with the kits. While building, a few people may be inclined to ask questions about what is available in the kit, what each component does, and how they have been used. Still, most will focus on just building models, and as the novelty of the kit fades, they are done with the kit. A tinkering kit with a nurturing environment can allow students to build their ideas into the physical world on their own. It's more like a tool to think with. This manual and models-based approach does not trigger or question the ability of what can be done with the components other than just building the specified models.

Being a tinkerer, I associate this way of exploration and learning. Tinkering is a disposition based on inquiry with the problem and solution space, further mapping it to one's associated knowledge of problem-solving methods. It has been driven by curiosity regarding the elements of the problem and solutions environment. For me, it's not just limited to solving problems but a habit of building and experiencing since childhood. I would play out my imagination by creating toys from soap boxes to bricks, trying to make them real. I had a preference for projects to understand the subjects better. Labs have been more exciting for me than theoretical lectures. Eventually, I realised that such an explorative and iterative approach, driven by my ideas and thoughts, worked for me. If I had a fair idea of how things work and used things around me, there would be a lot of ways to solve problems in a good and efficient manner. Tinkering, to me, is not just not limited to engineering design. Instead, it enables a learner with the skill of approaching the unknown and being able to explore and gain experience. It could be an experience of direct physical interaction or in a simulated environment too. I think tinkering is worth experiencing because it's one of the practices that can help deal with ill-structured problems. Tinkering has been known as a mindset, something that can be nurtured, not taught. Certain aspects are at play, like the environment, mentor support, and nature of the problem, which can support activities that encourage tinkering. So, considering those, if we design an environment, which provides open-ended problems, has scaffolds, tinkerable resources and just enough mentor interactions, we can allow the learners to try tinkering as one of the problem-solving approaches. So not by instruction but by scaffolding, designing the problems and the environment in a certain way, one can experience problem-solving with tinkering. Through a number of such experiences, one could build a habit of tinkering, and for whom it seems natural, it becomes a mindset or a disposition of looking at things.

1.2 Research Goal

Based on the discussions above, there is merit in designing a learning environment to nurture tinkering as a problem-solving strategy for engineering design problems. We start by asking how to nurture tinkering as a means of problem-solving in engineering design. To do that, we need to know what tinkering is and how it can be used for problem-solving. Then there is the question of designing a learning environment based on our understanding of tinkering and factors that influence the processes of tinkering when solving an Engineering Design problem. A learning environment could be a physical space or software designed to support learning a particular topic or concept. Also, there was a need to design a pedagogy that could be used to operationalise tinkering for problem-solving in engineering design. Hence primarily, our research objective is to *"design a learning environment for nurturing tinkering in the context of problem-solving in engineering design."*

1.3 Methodology

To achieve our objective, we divided it into two parts. The first was to look at the features of the learning environment leading to some mediating processes of tinkering, and the second was to ensure the procedures were leading to expected outcomes based on the learning dimensions framework. Hence our research questions (RQs) that emerged from the research objective are:-

- **RQ1: What features and activities should a learning environment contain to nurture tinkering?**
- **RQ2: How does the learning environment lead the learners to tinker?**

In this research, we followed design-based investigation (DBR), a flexible and pragmatic research methodology that allows the incorporation of all the stakeholders and the real-world context into the design and evaluation of interventions (Barab & Squire, 2004; Cobb et al., 2003).

Each iteration of DBR has three phases, namely Analysis/Exploration, Design/Construction and Evaluation/Reflection (Reeves, 2006). In this thesis, we conducted two iterations of DBR. In the first iteration, we focused on understanding and designing for tinkering as an approach to solve engineering design problems through our pedagogy and the first version of the learning environment (LE) we call "Tinkery 2.0". We used a conjecture map to structure and analyse the designed feature of the learning environment (Sandoval, 2014). In this first cycle, we focussed on the features of the LE (embodiments) (Sandoval, 2014) and the mediating processes they support. The findings from the first research cycle provided evidence for some features and uncovered challenges, thus providing suggestions for the redesign. The second iteration focused on understanding the challenges and redesigning the LE. In the next cycle, we examined the new design conjectures related to the refined solution. We analysed our study data to find evidence to support the theoretical conjectures that connect the mediating processes responsible for the outcomes.

Hence we could claim that the mediating processes, nurtured by the embodiments of the LE, resulted in the expected outcomes of a tinkering-based approach, which have been discussed in the research literature (Petrich et al., 2017).

1.4 Scope

Problem-Solving: In line with the objective of this research, suggestion from literature for domains where tinkering is considered an authentic practice, the available expertise and the researcher's experience, we scoped the domain to problem-solving in engineering design. To contrast the structured nature of the engineering design in labs, we choose to remain in the engineering design domain.

Context: Within engineering design, we choose robotics as our context based on its popularity in events like hackathons and workshops, which aided in better availability of literature, resources, and expertise. Furthermore, with the experience of the researcher and the availability of participants in the vicinity, we designed our learning environment for solving engineering design problems in robotics.

Technology: For the learning environment, we chose Lego Mindstorm EV3 as the kit for our resources as it is designed based on the characteristic of tinkerablitity. Moreover, it is a tried and tested kit for robotics, given the number of research studies in making and tinkering. The programming interface is scratch programming based, which again aligns with the characteristics of tinkerability; moreover, by limiting the type of building resources, i.e., the kit, we as researchers have been able to develop a thorough understanding of the resources and their affordances, which will help us interpret the learners' interactions with these resources. The limitations in scaffolding and problems available with most engineering design kits were also a reason to choose an engineering design kit, though reasonably recently (during the making of this thesis), Lego has changed its approach and moved to a problem-based pedagogy for its next generation of kits which is the successor to the Lego Mindstorm EV3 kit we have used.

Learner Characteristics: The studies were advertised as a Lego Mindstorms workshop, and tinkering was not mentioned in any communication before or during the study. The participants were undergraduate engineering students from any institute or university in India from mechanical, electrical and computer science engineering disciplines. Further, there were no limitations in terms of domain knowledge or experience with robotics.

1.5 Solution Overview

For designing a LE for nurturing tinkering as a solution approach for problem-solving in engineering design, we started with developing our pedagogy Xpresev (to be read as expressive). We used it as the basis of our learning environment named “Tinkery " (an adaptation from a nursery that nurtures plants by providing them with a conducive environment to grow) designed in the context of robotics. The components of Tinkery are an ordered set of open-ended problems with multiple possible solutions, the resources, which in our context are the Lego Mindstorms kit, a number of scaffolds and the various roles a mentor assumes. The Xpresev pedagogy orchestrates the activities in the LE.

1.5.1 The “Xpresev” Pedagogy

The name “Xpresev” (expressive) is derived from the combination of the words “Explore, Solve, and Evolve”, which have been identified as three operational aspects of tinkering and hence are the objectives in the design of the pedagogy. The overall aim of pedagogy is to make the learners express their ideas in the physical spaces hence the connotative name that sounds like “expressive”. This pedagogy has been designed to guide teaching-learning interventions incorporating problem-solving with tinkering or learning by problem-solving with tinkering. The following are the three objectives of Xpresev:-

Explore: The features of free exploration to capture intrinsic motivation have been incorporated in the explore phase. In exploration, learners start with small problems, which require them to interact with the physical space using the components available in the surroundings to solve the given problem.

Solve: Focuses on providing the means of externalising a learner's idea with the resources available in the surrounding. This can be done by allowing the learners to start building solutions for small component problems by using the affordances of materials explored in the previous phase and using them to externalise their ideas.

Evolve: Get the learners to evolve their solutions ideas by managing complex rents of a similar problem. This is done by scaffolding their reflection on their experiences in exploring, solving, and performing iterations of playful exploration and experimental play with available resources and ideas.

From the learners' perspective, learners have the freedom to explore, solve or evolve in any of the sessions. Still, the objective of the problems, the role of the mentor, his/her interactions and the scaffolds are designed to aid the objective of that session. The focus governs the design of Tinkery 1.0 and 2.0, whereas the learner might do all three in every session and various macro and micro levels in their problem-solving approach.

1.5.2 Learning Environment: "Tinkery 2.0."

Our learning environment Tinkery is currently designed for the context of problem-solving with robotics. It comprises 1) a set of open-ended problems with multiple possible solutions progressively ordered in complexity, situated in the physical context of the learning environment; 2) tinkerable resources, which in our case is the Lego Mindstorms kit that's a widely used robotics kit build in accordance to the requirements of tinkerable materials; 3) scaffolds like partial-manipulables, physical arrangement of resources based on their functional affordance, demos for introductions to features that support quick experimentation and freedom to access operational information from available documentation or the internet and 4) guidelines for the mentor which has been classified as prompts, triggers, and action through means of question, analogies or demonstration which are given based on learners state or actions. Fig. 1.2 provides an overview of the learning environment and its components.

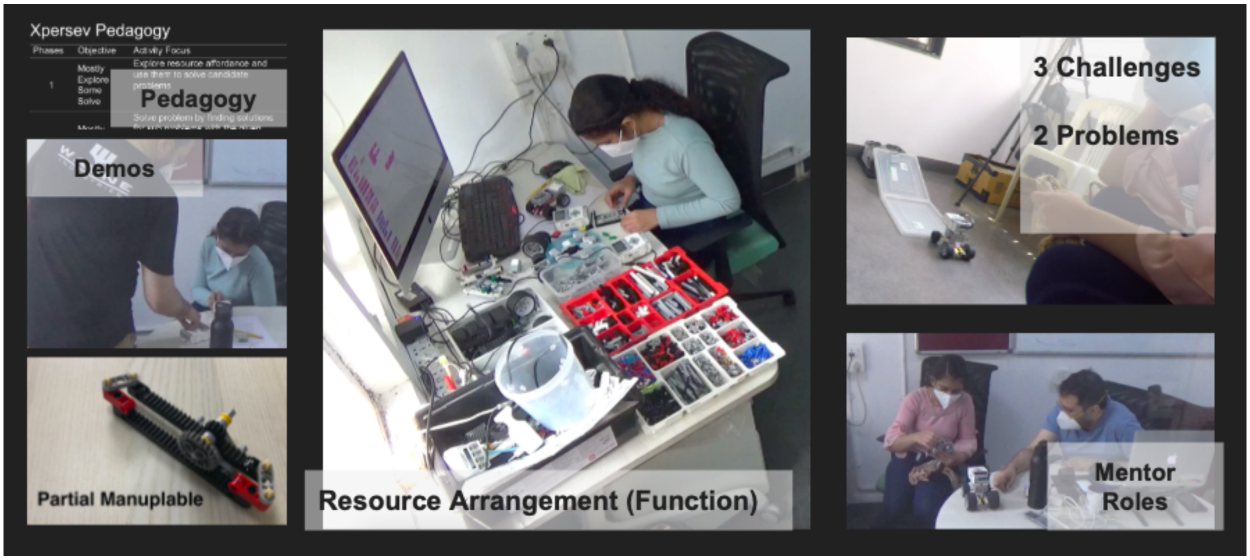


Figure 1.2: Overview of tinkery in its version two.

1.6 Contributions

The primary contribution of this thesis is the pedagogy “Xpresev”, the learning environment “Tinkery 2.0”, the role of a mentor in nurturing tinkering and guidelines for designing a tinkering-based LE. When working with Tinkery 1.0 and 2.0, learners have been seen to tinker when solving engineering design problems. This research contributes to the existing knowledge of the design and development of learning environments that support tinkering, specifically in terms of activity design, scaffolding, pedagogy and the role of a mentor for nurturing tinkering to solve problems in engineering design. These contributions also ensure learners' agency in problem-solving for tinkering to happen. Regarding tinkering as an individual activity, there has been a lack of recommendations regarding the pedagogy and the role of the mentor. Hence this research contributes towards the gaps in the design and use of tinkering kits. The thesis also emphasises the importance of making one's idea tangible and recommends doing so by building the ideas as physical artefacts to perform epistemic action, which uncovers challenges and reduces complexity.

Additionally in the thesis, we also recommend performing actions physically on the tangible artefacts and manipulating these tangible ideas in the form of pragmatic actions to reach the goal required for solving the problems. Research in problem-solving and learning with tinkering-based pedagogies can use this to enforce the creation of tangible artefacts to reduce complexity. Through literature and expert characterisation, we built an understanding of nurturing of tinkering to solve problems as iterative cycles of playful exploration and experimental play leading to an evolved understanding of the problem and solution ideas. This understanding helped us to develop Xpresev and Tinkery and can be used as an analysis lens further to develop theories, pedagogies and teaching and learning methods using tinkering. Further research in collaborative environments on making and tinkering can use these to analyse the dialogue between participants and the actions that follow as they share physical representations of ideas. These contributions have implications for researchers working with tinkering from the point of view of learning science, maker space, creative problem solving and engineering education under the broad umbrella of educational technology.

1.7 Organization of the Report

- Chapter 2 describes the related work problem-solving in engineering design making and tinkering. In Chapter 3, we describe our overall methodology. It begins by describing our chosen methodology to answer our broad RQ and moves on to the studies we did to answer our specific research questions. Chapters 4 and 5 describe the first iteration of DBR. Chapter 4 describes the problem analysis phase, wherein it discusses a few explorations and analysis of experts' points of view of tinkering as a practitioner and instructor. Chapter 5 describes the design and evaluation phase of the first version of Tinkery. Chapter 6 describes the second iteration of DBR. It describes the problem analysis phase of iteration 2, along with the design and evaluation of the revised version of Tinkery. Chapter 7 summarises the results and reflections of all our studies and discusses this research's claims, limitations and generalisability. Finally, in Chapter 8, we discuss our contributions and future work.

Chapter 2

Literature Review

As the focus of this research is tinkering for problem-solving in engineering design, in this chapter, we begin by understating tinkering and the numerous ways it has been used in various contexts. We also look at concepts related to tinkering, like bricolage and jugaad. Based on our understanding of referencing this literature, we put forward the definition of tinkering used in the rest of this thesis. Then we explore research on various tools, strategies and models for designing learning activities to promote tinkering. On a parallel thread, we survey the literature on problem-solving and focus on how it has been defined based on structure, associated cognitive processes and challenges faced by learners, especially in engineering design. The analysis of this literature gave rise to gaps in the current practices of tinkering for solving engineering design problems. It helped us determine how tinkering could be nurtured to help learners engage in tinkering to solve engineering design problems.

2.1 Understanding Tinkering

Tinkering has been defined using various perspectives in literature. Tinkering has been considered a source of ideas and models for improving the skill of making, fixing and improving mental constructions (Papert 1993); as a "playful, experimental, iterative style of engagement, in which people are continually reassessing their goals, exploring new paths, and imagining new possibilities" (Honey 2013); as a "mindset of solving problems through direct experience, experimentation and discovery" (Martinez 2013); and as " the generative process of developing a personally meaningful idea, becoming stuck in some aspect of physically realising that idea, persisting through the process and experiencing breakthroughs as one finds a solution" (Bevan 2015). As we dive deep into the literature, we see tinkering has been characterised based on its nature of activities and goals in terms of its visible processes and the practitioner. We now look at these various aspects one at a time.

2.1.1 Nature of activities

Tinkering has been associated with a set of manual activities, such as manipulating objects (Baker et al., n.d.; Godwin et al., 2016). Tools used in such activities have been emphasised (Erinosho, 1997; Richardson, 2008). These activities involve the rapid prototyping of ideas, and information gathered during each prototype drives subsequent trials (Resnick & Rosenbaum, 2013; Turkle & Papert, 1990; Wilkinson et al., 2016).

2.1.2 Goals

The antecedent condition of tinkering is the goal of producing a product or outcome (Petrich et al., 2013; Wang et al., 2013). The goal can be prescribed or emergent and shift over time (Berland et al., 2013; Roth, 1996), but the goal should be open-ended enough that there are multiple outcomes and solution paths (Jonassen, 2000). Tinkering contrasts with deliberate sensemaking, a more systematic and planned activity (Tuminaro & Redish, 2007; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001). The goal of deliberate sensemaking is deeper conceptual understanding. In tinkering, the goal of producing an outcome can sometimes drive deliberate sensemaking, but during tinkering, deliberate sensemaking happens only in service of the outcome. (Quan & Gupta, 2019)

2.1.3 Visible Processes

Observations of students tinkering to solve problems show that it emerges within interactions between students and their in-the-moment goals and is sustained by feedback from the social and material environment. (Quan & Gupta 2019). The literature on bricolage describes a bricoleur using an inventory of semi-defined elements which are at the same time abstract and concrete. They carry meaning, given to them by their past uses and the bricoleur's experience, knowledge and skill, a meaning which can be modified, up to a point, by the requirements of the project and the bricoleur's intentions (Louridas, 1999). The definition of tinkering as an iterative approach aligns with bricolage, a problem-solving process in which one adapts and modifies the solution as one goes (Louridas, 1999; Turkle & Papert, 1990; Vallgårda & Fernaeus, 2015).

2.1.4 Orientation

Tinkering activities have been suggested as having a playful orientation toward an activity (Bevan et al., 2015; Martinez & Stager, 2013; Resnick & Rosenbaum, 2013; Vossoughi et al., 2013; Wang et al., 2013). Orientation refers to a holistic sense of how students approach the activity (Martinez & Stager, 2013; Quan & Gupta, 2019; Vossoughi et al., 2013). Researchers define tinkering orientation as a playful approach and a general sense of trying things out. Tinkering has been considered a novice and expert practice, which sets it apart from most classroom practices (Danielak, 2014). It does not make tinkering better or worse, but it does make it an authentic professional practice (Berland, 2016). Tinkering involves providing the opportunity to work in a real-time environment with immediate feedback on actions taken.

2.1.5 Bricolage and Jugaad

Several terms with a similar meaning have also been associated with tinkering. Two of them are Bricolage and Jugaad. Both these terms have varied origins, but their meaning has a close resemblance but subtle differences with tinkering.

The literature mentions *bricolage is the creation of structure out of events. Bricolage has been discussed as the science of the concrete which applies logic to immediate sensory percepts, and it thereby becomes a logic of the concrete".*(Louridas 1999, Lévi-Strauss, 1962), The idea of an inductive approach seems to be conveyed here, which derives from concrete experience. One would argue about its placement with design. The literature further argues that the *"view of design as bricolage suggests a middle way: that science and design follow the same mode of work, but they apply it in different contexts".* (Louridas 1999, Lévi-Strauss, 1962) This could be interpreted as bricolage being a stance of altering between the inductive and deductive approaches throughout the process of making or building something. Further, the literature suggests,s "*A bricoleur is a person who makes do with what's there, with what one encounters".* This interpretation has been expressed as a way of doing things or an attitude towards doing.

Similarly, when referring to research from the literature on solutions with jugaad came to be known as non-conventional, frugal, more of a hack or an innovative quick fix or a simple work-around. These solutions bend the rules or use a resource uniquely (Bhatti, 2013; Prabhu et al., 2013). Similarly, jugaad is about doing more with less. It often signifies creativity to make existing things work or to create new things with a meagre of resources. Jugaad has developed under constrained circumstances where constraints may be in resources, rules, economics or exposure. The constraints could be self-imposed, where someone is cautious about the way they use certain resources. A mix of situations where people faced a lack of resources or were cautious about their use has used jugaad as a way of life. Being able to do jugaad is a quick rush of success, the victory moment, and in some cases, a lot of appreciation and recognition (Prabhu et al., 2013). This drive to be able to solve challenges with a workaround or a quick fix becomes a part of life in constrained environments. One uses it to bend the rules or work around problems; more importantly, for the less privileged, it is the means to survival (Beatrice, 2014). Recently, we have seen much research on the essence of such strategies in business and production to allow creativity. Juggad is becoming a global phenomenon (Rai, 2019). Though jugaad has been criticised for being a product of poverty and underpins path dependencies stemming from dilapidated infrastructure, unsafe transport practices, and resource constraints, calling it a system risk (Thomas, 2011) when we look at it as a connotation of tinkering, we see jugaad as the starting of tinkering where tinkering in its spiral evolutionary nature evolves the jugaad solution.

2.1.6 Defining Tinkering

We started with the various definitions of tinkering, as discussed at the beginning of section 2.1, which talks about it either as a goal or nature of activities or processes or orientation. Given the lack of a holistic definition, we define tinkering based on these four characteristics as *Tinkering is evolving a solution by building experiences of exploration and play.* Here exploration and play is the attitude with which one tinkers. Building experiences refers to the visible processes of tinkering through which one takes actions to get an outcome which is the experience they build. The nature of the activities that tinkerers do leads to the evolution of the solution, which is the goal of tinkering. The summary of this literature and the connection with the definition has been summarised in Fig. 2.1.

2.2 Current Practices in Tinkering

Many current practices associated with tinkering claim to be using or teaching tinkering by providing challenges that must be solved in a given time. They do subscribe to open-ended problems and allow rapid prototyping but do not focus on tinkering as means of problem-solving.

Hackathon is one such setup, but they are more result or product-oriented than focusing on supporting or nurturing tinkering to solve engineering design problems (Happonen et al., 2020). Similarly, workshops focus on technological processes or skills (Hielscher & Smith, 2014), whereas most tinkering workshops we explored tend to focus on teaching design thinking. Most of their curriculum is designed on the principles of design thinking being lectured, whereas tinkering may be emergent or incidental if the right combinations of people and the environment come together. The focus has always been on developing or learning new technologies or processes (Hielscher & Smith, 2014) and not tinkering.

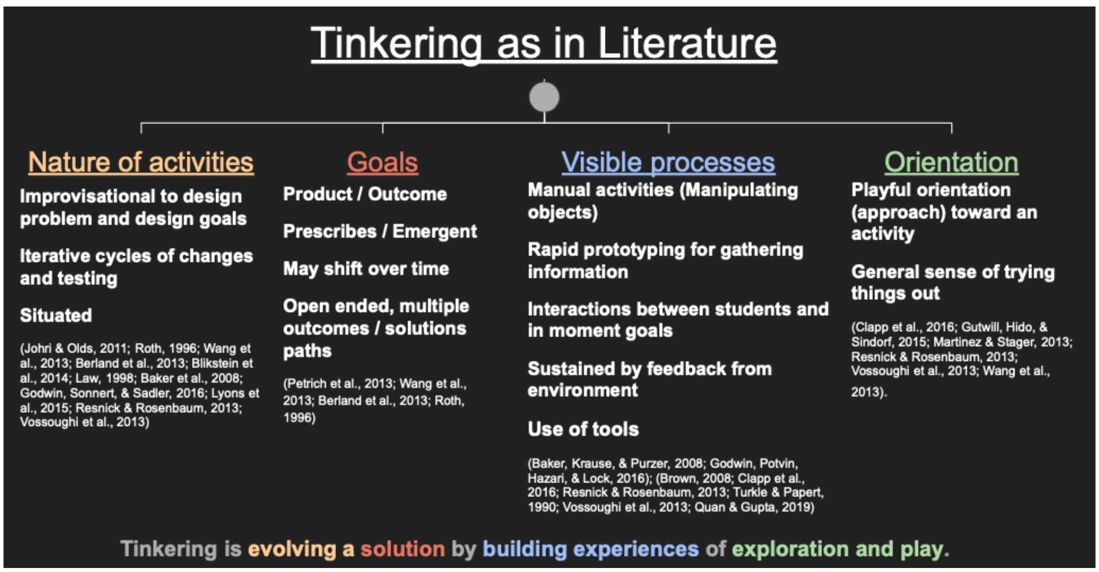


Figure 2.1: Summary of tinker based on its characteristics and its implication of our definition of it.

The other classical practice widely associated with bricolage is the master-apprentice driven by self-motivation (Brown et al., 1989) towards domain/problem. The challenges of such a model are the number and durational availability of experts. A number of informal spaces driven by the apprentice model have emerged as maker and tinkering spaces. Still, these, especially in the engineering domains, are primarily driven by a group of people with a common interest or as a part of an engineering mission (Sheridan et al., 2014; Vossoughi & Bevan, 2014). Problem-solving is primarily driven by the curiosity and personal interest of the people who work there, supported by the group's senior members. Most of the workshops they conduct are on conceptual knowledge and technology transfer. Formal labs like the ATL (*ATL*, 2019) in India provide resources, but problems depend on the lab's mentors. The mentor training document focuses on conceptual teaching and teaching them design thinking and lacks insight into their roles in nurturing or tinkering (*Teacher Training, ATL*, 2016).

The most widely known and accepted way of learning to tinker is to work with tinkering kits. These kits have been widely used and distributed to encourage making, building and tinkering in the disciplines of science, technology, engineering, arts and maths. The tinkering kits can be classified as primarily a set of resources, instruction manuals, some problems and the pedagogy they are built upon. Literature suggests that the resources of tinkering kits should subscribe to the requirements of tinkerablity to allow tinkering to happen (Resnick & Rosenbaum, 2013). Not all kits labelled as tinkering kits have resources that are tinkerable (Ruzzenente, 2012; Jung, 2018). Lego is one tinkering kit that has been built based on the requirements of tinkerabilty. Most kits come with instruction manuals and step-by-step guides to making a model. Most of them do not have worksheets that can act as prompts for reflection on the affordance of the material. Some kits prove problems to be solved by building something. Still, for most problems, solutions are given as pre-designed bots for whom the step-by-step instructions are available in the manual, not allowing the learners to try and explore to build their own solutions. Most manuals have specific bots to be built rather than having worksheets with reflection prompts, making the learners think independently and come up with different solutions (Martinez & Stager, 2013; Resnick & Rosenbaum, 2013). As researchers point out, there is a need for certain scaffolds to ensure play happens even when the resources support play (Honey & Kanter, 2013). Instead, these kits depend on the excitement towards using new technology (novelty) and assume problem-solving behaviours like tinkering will emerge as the learners keep engaging or playing with the kits. The pedagogy is a missing component of most such kits. Commonly followed methods of using such kits are project-based learning, where the idea harps on the excitement with new and exciting technologies as toys to drive the motivation to make more models following instruction. The idea behind it is that if learners make enough models with the manuals, they will get the hang of the resources, and tinkering will emerge, but it only happens if they reflect on their building process (Honey & Kanter, 2013; Martinez & Stager, 2013; Resnick & Robinson, 2017).

2.3 Designing for Tinkering

Whether students tinker depends on many contextual features - the environment, the task, other actors, and how students orient themselves to the activity in the setting. (Quan & Gupta 2019). In this section, we discuss the design of tinkering-based learning activities. First, we discuss the factors that influence tinkering as a strategy, and then we review models for designing learning activities based on tinkering.

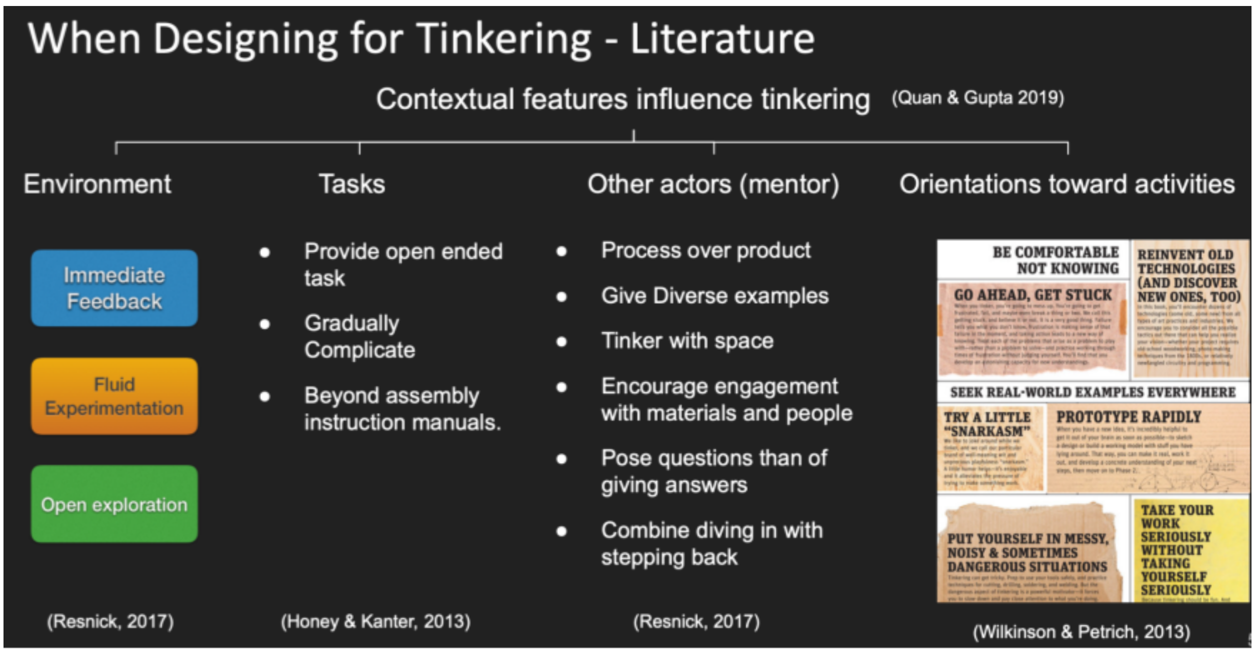


Figure 2.2: Summary of contextual features that influence tinkering.

2.3.1 Contextual factors influencing tinkering

Tinkerability (Environment): This refers to how tinkerable the resources are and how they support the processes of tinkering (Resnick & Rosenbaum, 2013). Learning technologies have been designed to encourage and support processes of making and tinkering. The following aspects must be considered when creating tools, environments and activities for students to tinker with.

- *Immediate Feedback:* In highly tinkerable construction kits, there is a very short interval of time between making a change and seeing its effect. Moreover, there should also be a provision for tinkerers to see the process.

- *Fluid Experimentation:* The quicker the iteration, the faster the generation and refinement of ideas. It should be easy to get started with the tool, and the components should be easy to connect. It should take less time for tinkerers to connect and set it up.
- *Open exploration:* The tinkerers should inspire people to explore a wide variety of materials and genres.

Tinkering ability (Actors): Research suggests encouraging certain practices will empower the learners and makers to exploit the tinkerable environments (Resnick & Rosenbaum, 2013). Following are a few such best practices, along with ways of implementing them:-

- *Emphasise process over product:* While making something is an important part of tinkering, too much emphasis on the final product can undermine the experimentation at the heart of tinkering. To engage people in thinking about the tinkering process, encourage them to document and discuss intermediate stages, failed experiments, and sources of inspiration.
- *Set themes, not challenges:* Rather than posing challenges to solve (as is typical in many design workshops), propose themes to explore. Select workshop themes that are broad enough to give everyone the freedom to work on projects they care about but specific enough to foster a shared experience among participants.
- *Highlight diverse examples:* Show sample projects that illustrate the wide diversity of what is possible, provoking people to think divergently.
- *Tinker with space:* Consider how you might rearrange or relocate to open new possibilities for exploration and collaboration.
- *Encourage engagement with people, not just materials:* In addition to having a "conversation with the material", tinkerers also benefit from having conversations (and collaborations) with other people.
- *Pose questions instead of giving answers:* Resist the urge to explain too much or fix problems. Instead, support tinkerers in their explorations by asking questions, pointing out interesting phenomena, and wondering aloud about alternative possibilities.

- Combine diving in with stepping back: While it is valuable for tinkerers to immerse themselves in the process of making, it is also important for them to step back and reflect upon the process.

Nature of problems (Tasks): Tinkering is most likely to happen if the nature of the tasks compliments the characteristics of thinking. The task should provide opportunities for the process of tinkering to emerge, as only then can the learners take the attitude of tinkering towards completing the task (Honey & Kanter, 2013). The following guidelines on the nature of problems/tasks will provide learners with opportunities to tinker: -

- *Provide open-ended tasks*: The tasks should allow a wide variety of solution approaches. Regarding design problems, multiple possible solutions should be reached in different ways. This allowed the learners to personalise their learning process and incorporate their ideas into the solutions, which is powerful in building confidence and learning in the process.
- *Gradually complicated tasks*: If one intends to provide a complex problem requiring a higher degree of knowledge and skill for the given set of learners, it is advisable to give an ordered set of problems that will lead to the complex problem. The initial problem can be very specific, like performing a task to make the learners experience the conceptual knowledge and skills, eventually leading to open-ended problems of similar nature and then giving the complex problem to be solved. The initial problem acts as a scaffold allowing the learner to gradually move towards the skill and knowledge required to solve the complex problem.
- *Go beyond assembly instructions*: Though instruction manuals are useful, there must be ways to enable reflection when using them to build a given model. The reflection should get the learner to think about the affordances of the components as they are building them. Another way is to let the learners figure out how the components work by allowing them to explore and play while scaffolding them to build something of their liking. This process can be assisted by a mentor who enables reflection and nudges them to try components and build their ideas.

Nature of Practices: Tinkering is about the practices one does and the attitude with which they are done (Wilkinson & Petrich, 2013). Following are a few such recommended practices.

- *Be comfortable not knowing*: The idea of tinkering is figuring out things, and not knowing is where we start. Hence one must be comfortable with this state, and as one gradually tinkers, one builds confidence in eventually figuring out things. It is ok to avoid knowing things and figuring them out as the requirement emerges.
- *Get stuck*: Since tinkering is about wandering into the unknown, there are a number of times when one gets stuck in a situation or a problem or in a process. The idea is to be comfortable about being stuck, even if it is a failure. As tinkering is about figuring out things, there are opportunities that help us reflect and gain insights into the process and ideas. So it's recommended to be comfortable getting stuck as one eventually figures out a way of getting out of it.
- *Create rather than consume*: The essence of tinkering is in taking action and then figuring out things. Hence instead of just using things, one must also focus on how things work and create versions better suited to one's needs.
- *Express ideas via construction*: Tinkering is about actions in a solution space; hence one must materialise them by constructing them physically.
- *Use familiar materials in unfamiliar ways*: The world is full of stuff that was invented to do a specific job. Taking a common object and putting it to new use will likely result in surprises.

2.3.2 Models of Learning by Tinkering

Creative learning spiral (CLS): Researchers have stated that children imagine what they want to do, create a project based on their ideas, play with their creations, share their ideas and creations with others, and reflect on their experiences – all of which leads them to imagine new ideas and new projects (Resnick, 2017). CLS has been represented as a spiralling process in which children transition between the stages of imagining, creating, playing, sharing and reflecting (Fig 2.3).

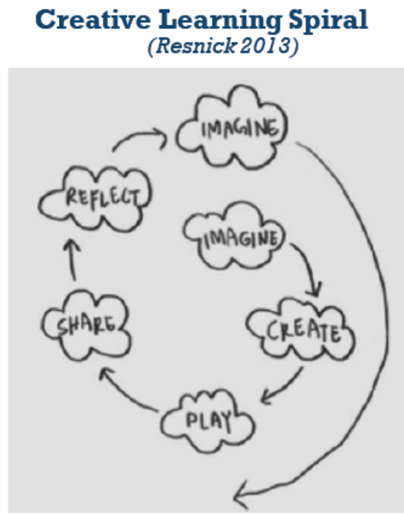


Figure 2.3: The creative learning spiral. (Resnick, 2013).

This has primarily been used in school and tinkering activity centres for school kids. A number of scratch-based activities have been designed on the creative learning spiral (Resnick & Robinson, 2017). This model focuses on fostering creativity, and tinkering has been a medium to do so.

Think, Make and Improve: Another model called Think, Make and Improve (TMI) (Martinez & Stager, 2013) claims classroom making is less concerned with producing a perfect product or finding one solution to a problem. The most profound learning experiences may occur while en route to producing a product. The model consists of three stages, namely "Think", which incorporates problem-setting, brainstorming, and planning processes; "Make", where most action happens in building or creating artefacts or experiences; and "Improve", which is a result of a state of being stuck in which case there are actions to come out of that state or learners have achieved their goal and may want to improve on it.

The process ends when the maker is satisfied with the product or accepts the current state as the final. One could come back and still improve the product later. The authors claim there is always a scope for improvement. This model has been used extensively in the making and derives actions from being taken using a tinkering mindset but does not talk about the nuances of the mindset itself.

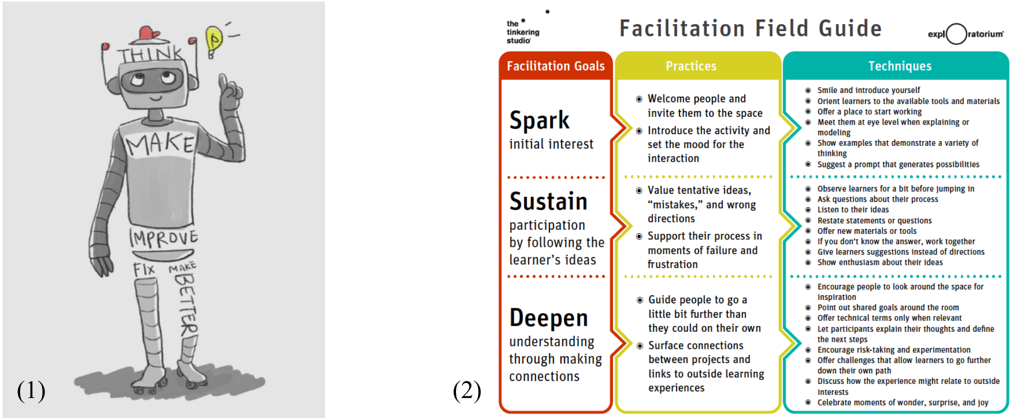


Figure 2.4: (1) Think Make Improve: Primary focus is making and tinkering is emergent in activities (Martinez & Stager, 2013) (2) Primary focus is designing activities for conceptual learning with tinkering problem solving is just an optional aspect (Wilkinson & Petrich, 2013).

Spark Sustain and Deepen: Another well-known model is Spark, Sustain and Deepen (Harris et al., 2016; Wilkinson & Petrich, 2013): The researchers here discuss a three-phase approach towards guiding the exploration activities for learning with the experience of building something.

To spark is to orient learners to the space and activity at hand while establishing the safety needed for participants to take risks and unleash creativity. To sustain is maintaining participation by offering new tools or suggestions, welcoming learners' ideas, re-engaging participants when interest waned and revoicing ideas to help clarify the nature of the problem. To deepen is deepening the participation by fostering reflection or challenging learners to complexity their work. The authors align each of these phases to the practices and techniques to ensure those practices. The learners are expected to approach the activity with a making mindset. Researchers have provided extensive guidelines for teachers to adopt this model into their pedagogy. The instructions have been claimed to guide the learners with a tinkerer's mindset towards exploration. The authors have also provided rubrics for evaluating learning in various dimensions while using such a pedagogy. Researchers talk extensively about developing a tinkering approach but limit to providing guidelines, with the primary focus is learning.

2.4 Engineering Design

2.4.1 Ill-structured Problems and Engineering Design

There is general agreement among researchers in problem-solving that problems can broadly be classified into two types, namely well-structured and ill-structured problems(Fernandes & Simon, 1999; Jonassen, 1997, 2000). A problem has three components: an initial state, a goal state and a method or procedure to eliminate the gap between these two states. For a well-structured problem, these three components are either clearly identified in the problem description or familiar based on the information given in the problem statement(Jonassen, 1997, 2000; Maloney, 2011; Pretz et al., 2003). Ill-structured problems are those for which some or all of the three components of a problem need to be clearly defined or evident from the problem description(Fernandes & Simon, 1999; Jonassen, 1997, 2000). Real-world problems like engineering problems, life decisions, house design, art creation, etc., fall into this category. For design problems, the two states and a method to go between the two states might not be completely known; hence they have been classified as ill-structured problems (Jonassen, 2000).

When comparing the characteristics of ill-structured problem-solving with that of tinkering, we see that ill-structured problem-solving is influenced by context (Jonassen, 2000), and tinkering has been known to happen in context (Baker et al., n.d.). Ill-structured problem-solving requires interacting with the environment (Fernandes & Simon, 1999; Jonassen, 2000), and when people tinker, they interact with their goals (which are based on the problem requirement) and environment while they are working in it (Baker et al., n.d.; Godwin et al., 2016). Ill-structured problem-solving requires external scaffolding or support to sustain problem-solving processes (Fernandes & Simon, 1999; Kothiyal, 2014), whereas tinkering is sustained by dialogue between the tinkerer's goals and actions they take in the physical space, which scaffolds their problem-solving process (Resnick & Robinson, 2017). Ill-structured problem-solving sometimes involves creating and using external representations, which are important in reducing ambiguity (Kothiyal, 2014). Tinkering emphasises the creation of artefacts and performing the action to attain desired goals (Vossoughi & Bevan, 2014). Ill-structured problems have incomplete ambiguous goals (Kothiyal, 2014), and goals in tinkering can accommodate the ambiguity as they could be prescribed or emergent, which may shift over time (Turkle & Papert, 1990).

Research in engineering design has documented iteration and experimentation to support knowledge generation and refinement of designs (Dym et al., 2005; Vossoughi & Bevan, 2014). Rapid prototyping, the generation of manipulable external representations of early design ideas to refine the design (Berland et al., 2013; Brown, 2008; Guerra, Allen, Crawford,& Farmer,2012), is a design practice that overlaps with tinkering as an improvisational, iterative process toward design goals (Baker et al., 2008; Godwin, Sonnert, & Sadler, 2016). In design problems, the goal is to produce an artefact or solution, the criteria for success need to be better defined, and the problem can be solved with multiple solutions. The engineering design process involves a multiplicity of practices and approaches to complex problems (Dym et al., 2005), and one is likely to engage in many of these in the course of designing a solution to a complex problem.

2.4.2 Problem-Solving Strategies in Engineering Design

General problem-solving strategies have three major steps; problem representation, search for solutions and implementation. The strategy used to solve a problem will depend on its structure.

As engineering design problems have been identified as ill-structured, one may approach them in two ways. One is a top-to-bottom approach with a mix of depth-first and breadth-first approaches. The solutions process in such a case would require understanding the design specification, problem reduction (subgoals), designing high-level solutions for each subproblem, decomposing high-level solutions to concrete sub-problems, and solving substantial sub problems sequentially(Hmelo-Silver, 2004). Engineering design problems can also be solved opportunistically (Guindon, 1990), which is the second way, or at least till a proper design decomposition is discovered to continue with a top-to-bottom approach. Opportunism arises from recognising a partial solution, adding constraints to solution space possibilities, finding new inferences and/or goals to reduce ambiguity, drifting through partial solutions, and interleaving problem specification into solution development (Jonassen, 1997, 2000).

2.4.3 Tinkering as a problem-solving strategy for Engineering Design

Characteristics of tinkering align with an opportunistic approach, where tinkering talks about re-engineering and starting with partial solutions, adding constraints by working with what is available in the environment. (Vossoughi & Bevan, 2014). Tinkerers consistently modify their solution paths by evolving their design requirements based on the new inferences derived from their actions in the environment (Bevan et al., 2014). Every new interaction between their ideas and the environment is like a new opportunity they use to reduce ambiguity and reach a concrete solution requirement that fulfils the requirement of the problems (Martinez & Stager, 2013). Warranted by the overlap and connections between tinkering and other practices of ill-structured problem solving like engineering design, tinkering can be regarded as one practice within the broader landscape of the engineering design process (Quan & Gupta, 2019).

Tinkering has been seen as one practice within the engineering design process. Researchers (Wang et al. 2013) have shown that tinkering is productive for encouraging young children's engagement in brainstorming, testing, and refining design practices. We see a connection between tinkering approaches and what Jonassen (2000) refers to as a design problem. Like all engineering activities, tinkering is a situated phenomenon (Johri & Olds, 2011; Lave & Wenger, 1991; Roth, 1996; Wang et al., 2013). Whether students tinker depends on many contextual features: the environment, the task, other actors, and how students orient themselves to the activity in the setting. Tinkering emerges within interactions between students and their in-the-moment goals and is sustained by feedback from the social and material environment. Iteration and experimentation support knowledge generation and refinement of designs (Dym, Agogino, Eris, Frey, & Leifer, 2005; Roth, 1996). Rapid prototyping is the generation of manipulable external representations of early design ideas to refine the design (Berland et al., 2013; Brown, 2008; Guerra, Allen, Crawford, & Farmer,2012); as design practices that overlap with tinkering as an improvisational, iterative process toward design goals (Baker et al., 2008; Godwin, Sonnert, & Sadler, 2016). The engineering design process involves a multiplicity of practices and approaches to complex problems (Dym et al., 2005), and one is likely to engage in many of these in the course of designing a solution to a complex problem.

While tinkering is not widely used in engineering design literature (compared to terms such as troubleshooting and prototyping), aspects of tinkering highlighted above share commonalities with some design practices (Quam & Gupta, 2019). To conclude, Turkle and Papert (1990) argued for bricolage as a valid practice, regardless of whether it leads to a planned activity. They argue that some ways of knowing (e.g., bricolage) are authentic to some students and emphasise the value of multiple ways of knowing and learning, what they refer to as “epistemological pluralism”.

2.5 The Need for Designing to Nurture Tinkering

The literature review in this chapter (chapter 2) has shown that tinkering is a valuable tool/strategy for solving engineering design problems, and learners should engage in tinkering. A number of researchers have presented models and pedagogies for learning with tinkering, but guidelines for problem-solving with tinkering are limited to a few best practices. Moreover, as we saw at the beginning of section 2.2, the current practices, like hackathons, workshops etc., that claim to associate with tinkering do not design the activities or the environment even at the best practices level that scaffold or favour tinkering but entirely focus on solving problems and any tinkering that happens is incidental. The pedagogical design for solving problems with most tinkering kits and in most tinker labs needs to be aligned even for the best practices of nurturing tinkering. Additionally, most mentor training programs for conducting and supporting tinkering activities in a physical setting are limited to teaching design thinking practices. They need to talk about the support required for running tinkering. Hence, a learning environment that supports nurturing tinkering practices is required to enable learners to engage with tinkering.

Research on tinkering for learning and creativity has given us models and guidelines. When considering tinkering for problem-solving, especially in engineering design, there are only a few best practices with borrowed pedagogies. There is a need for a pedagogy that focuses on the learning aspects of exploration and play and the evolution of ideas, which is essential for problem-solving. We also need to consider tinkerablility, tinkering ability, nature of tasks and nature of activities when designing for tinkering. As we saw in the literature, tinkering compliments the nature of ill-structured problems and engineering design problems are ill-structured. Hence designing a pedagogy and learning environment with guidelines for tinkering-based approaches to solving engineering design problems can help engage learners to tinker to solve such problems. It will also allow them to use it as a primary or optional tool for problem-solving.

2.6 Summary

This literature survey of tinkering-based activities for problem-solving in engineering design led us to identify the gaps and situate the need for research in designing for nurturing tinkering. To begin our research towards designing LE for nurturing tinkering, we stepped back into the available literature on tinkering, making and explorations for teaching and learning STEAM using tinkering. We also looked at models and best practices for the design of tinkering-based learning activities. We also looked into the literature on problem-solving in engineering design and how tinkering is an appropriate option for solving engineering design (ill-structured) problems. The next chapter describes the methodology we adopted to attain the research objective.

Chapter 3

Research Methodology

In this chapter, we describe how we chose a research method to address our research objectives and discuss the features of the selected method and the process we undertook.

3.1 Choosing a Methodology

The objective of our research has been to design a learning environment for nurturing tinkering in the context of problem-solving in engineering design. To address this broad objective, we consider the following sub-goals:

1. Understand what tinkerers do when they tinker. Also, understand the influence of various factors like the environment, learners/mentors and the nature of problems on the tinkering problem-solving process.
2. Design a learning environment based on the understanding of tinkering and the factors that influence the processes of tinkering when solving an engineering design problem.
3. Analyse how the features of the learning environment support the processes of tinkering.
4. Refine our understanding of various factors influencing tinkering for solving engineering design problems.

Thus we require a methodology which is systematic to build an understanding of tinkering for problem-solving, yet flexible to allow for consideration of the complexity of building a learning environment by creating a harmony between the features designed, off-the-shelf kits, and the role of a mentor; and studying the effect of the interplay of these multiple features. These are the signature characteristics of a set of methods under the Educational Design Research (EDR) paradigm. The different research methods under EDR are Design-Based Research (DBR) (McKenney & Reeves, 2014; Puntambekar, 2018), Design-Based Implementation Research (DBIR) (Penuel et al., 2011) and Design and Development Research (DDR) (Richey & Klein, 2005, 2014). The problem of implementation, i.e., designing sustainable policies and programs in education, is guided by DBIR (Fishman et al., 2013; Penuel et al., 2011), while instructional programs, processes, and product design and development are guided by DDR (Richey & Klein, 2005). While DBR aims to “ refine problems, solutions, methods, and design principles." (Reeves, 2006).

Hence in our case, we choose to use DBR as a methodology which allows us to address dual goals simultaneously: one through designing and refining a learning environment and the second by iteratively coming up with a refined theoretical understanding of how learners tinker. These are signature characteristics of design-based research (DBR) (Puntambekar, 2018). Within the DBR iterations, we used the conjecture mapping approach, which helped us map the features of our learning environment to the learning processes they mediate and how they come together to produce a desired outcome (Sandoval, 2014).

3.2 Research Methods

3.2.1 Design-Based Research (DBR)

The initial interventions in educational design research often uncover challenges, so one needs to iterate and refine the development process until the results of the intervention are as expected, which is referred to as one research cycle. The reflection from each cycle informs the next cycle in DBR research. The iterative steps comprise analysis and exploration, design and development, and evaluation and reflection (McKenney & Reeves, 2014). A DBR cycle begins with the first "Analysis and exploration” phase. In this, the problems, context, stakeholders, and the existing solution is analysed through a series of literature reviews of empirical studies to gain an insight into characterising the problem. It is followed by the "design & development phase", where a preliminary solution is developed based on design principles and findings from the previous phase. This learning design is evaluated by several research studies that may employ quantitative, qualitative, or mixed data collection methods to produce design principles and enhance solution implementation, which is a part of the next phase, "evaluation and reflection".

3.2.2 Conjectures & Conjecture Maps

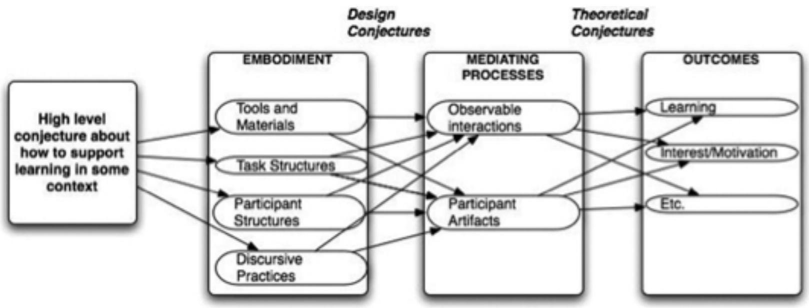


Fig 3.1 Generalized conjecture map for educational design research. (Sandoval 2014)

A Conjecture map is a research planning and organisation tool used in design-based research. The map contains six significant elements and their relationships: the embodiments, mediating processes, desired outcomes, design conjectures, theoretical conjectures, and high-level conjectures. Whatever the context, learning environment designs begin with some *high-level conjecture*(s) about how to support the kind of learning we are interested in supporting in that context. That conjecture becomes reified within an *embodiment* of a specific design. That *embodiment* is expected to generate certain *mediating processes* that produce *desired outcomes*. A research team's ideas about how embodied elements of the design develop mediating processes can be articulated as *design conjectures.* A team's ideas about how those mediating processes produce desired outcomes are *theoretical conjectures*. Each element and its relations are explicated (Sandoval, 2014). Fig. 4.5 shows a generalised version of a conjecture map.

3.3 DBR Iterations in this Thesis

We have conducted two DBR cycles in this thesis to design and refine the learning environment. In the first cycle of DBR, we focussed on the features of the LE (embodiments) (Sandoval, 2014) and the mediating processes they support. The findings from the first research cycle provided evidence for some features and uncovered challenges, thus providing suggestions for a redesign. In the next cycle, we examined the new design conjectures related to the refined solution and the theoretical conjectures that connect the mediating processes responsible for the outcomes. A summary of both the DBR cycles is shown in Fig. 3.2.

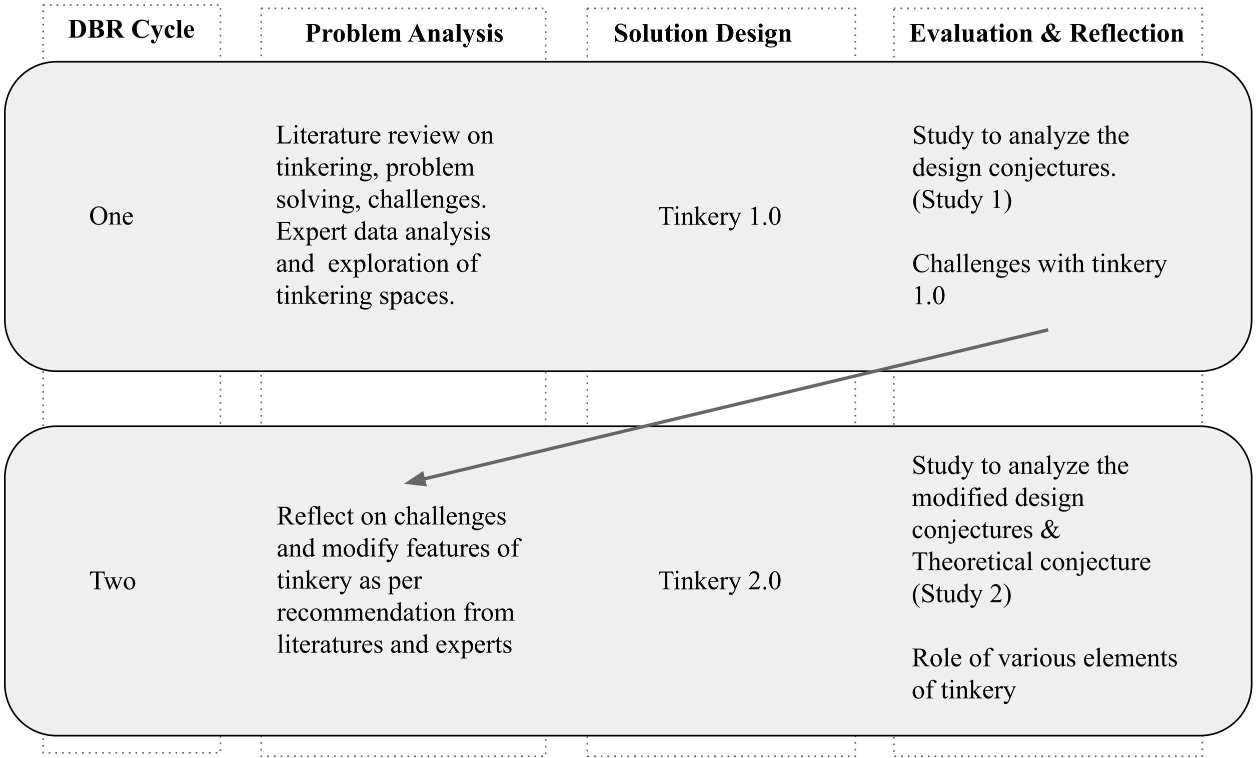


Figure 3.2: The design based research approach in developing Tinkery 1 & 2.

3.3.1 DBR Cycle one (Tinkery 1.0)

The goal of the first cycle of DBR was to develop an operational understanding of tinkering, the processes and nuances of tinkering, factors that influence tinkering and the possibility of using tinkering to solve engineering design problems. These were addressed in the problem analysis phase with the help of literature, analysis of monologues of expert tinkerers, and a few exploratory studies. By the end of the problem analysis, we had identified the theoretical basis and collated design guidelines for designing a learning environment for nurturing tinkering.

The solution design phase of cycle one focused on designing the “Xpersev” (to be read as ‘*expressive’*) pedagogy and the features of the learning environment “Tinkery 1.0” in its first version. To structure the design process of Tinkery 1.0, we used conjecture mapping, and for this cycle, we focused on developing design conjectures. This helped us centre our observation on the interactions between the features and the tinkering processes exhibited by the participants.

We conducted a study with Tinkery 1.0 wherein the design conjectures guided the data collection, i.e. the interactions of four participants with the features of the LE and the actions the participant performed during these interactions. The research question guiding this study was:

What *features and activities should a learning environment have to nurture tinkering?* These observations were analysed with the methods of interaction analysis to understand the role of LE features in the actions done by the participants leading them to mediating processes.

We concluded DBR cycle one with reflections on the study findings related to the features of Tinkery 1.0 that supported the mediating processes of tinkering, along with some challenges that had been uncovered. The summary of this DBR cycle is shown in Fig. 3.3.

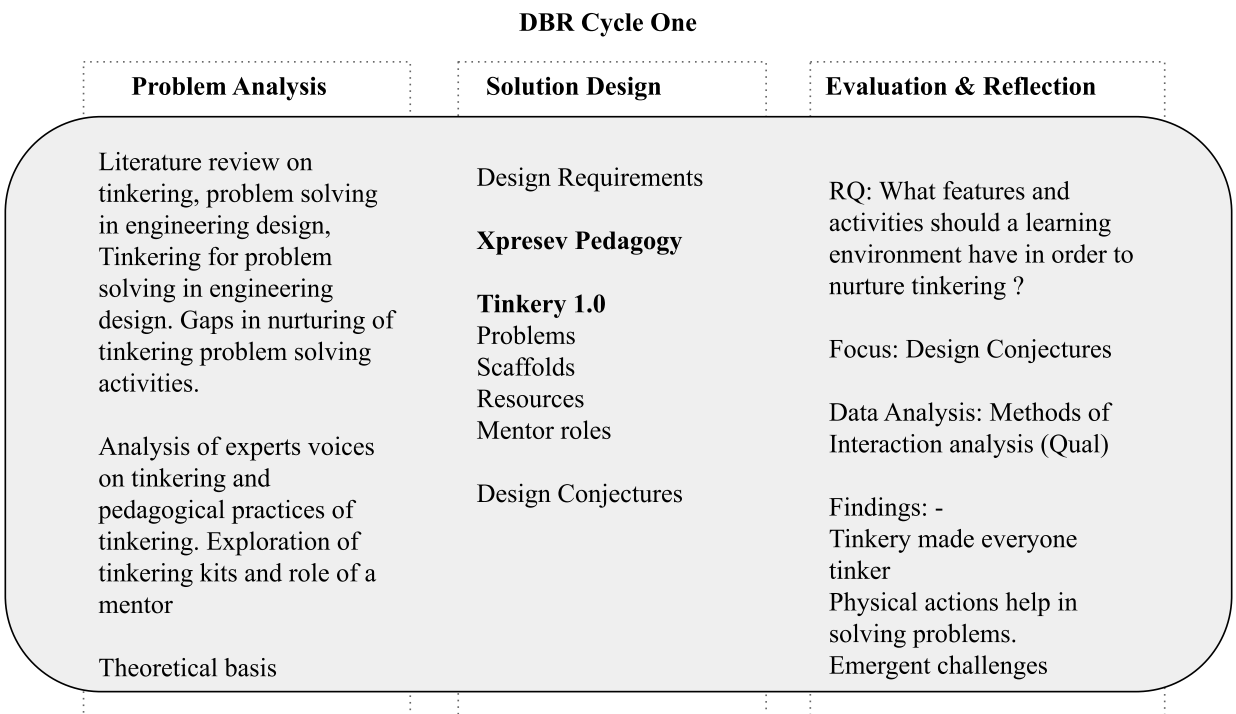


Figure 3.3: Summary of the first cycle of DBR.

3.3.2 DBR Cycle Two (Tinkery 2.0)

The goal of the second cycle of DBR was to refine the design of Tinkery 1.0 to address the challenges. We also sought evidence for the theoretical conjectures to examine if the mediating processes led to the expected outcomes from a tinkering-based process (Harris et al., 2016; Petrich et al., 2017). In the problem analysis phase, we addressed the emergent challenges from the previous cycle. We referred to recommendations from literature and experts, leading to changes in the design recommendations of the last cycle.

In the solution design phase of the second cycle, changes were made to certain features as per the changes in the design recommendations. This led to the evolution of Tinkery 2.0. For the second cycle, we focused on developing design conjectures for the changes made and the theoretical conjectures.

The study was conducted with Tinkery 2.0 and made observations based on the new and theoretical design conjectures. Continuing the primary research question, "*What features and activities should a learning environment have to nurture tinkering ?" For* this iteration, we specifically analysed the changes made to the features in Tinkery 2.0. We focussed on the interactions of participants with the features of the learning environment and the actions the participant performed during these interactions leading to the identification of various problem-solving processes. These observations were analysed with the methods of interaction analysis to 1) figure out the role of learning environment features in the actions done by the participants leading to the mediating processes and 2) understand problem-solving processes for their impact on the outcomes. The summary of the cycle is seen in Fig. 3.4.

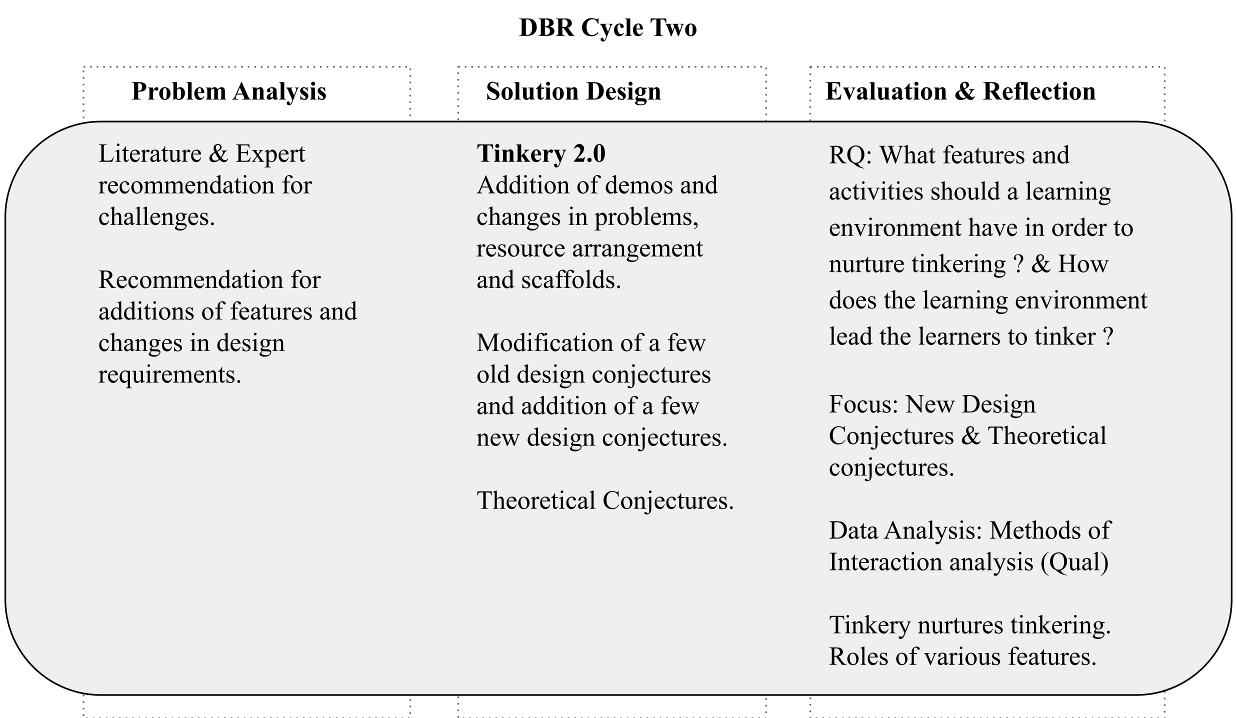


Figure 3.4: Summary of the second cycle of DBR.

3.4 Overview of Participants and Data Collection

The participants of our research studies were undergraduates and postgraduates from the disciplines of mechanical, electronics and computers. Few of them had experience working with robotics or building vehicles as part of competitions. We used a convenient sampling technique for all the research studies as part of this thesis work. The gender distribution in our studies was 50%.

For the first study, we recruited five students from 2 engineering institutes in India for a three-day workshop on Lego Mindstorms. They were recruited before COVID-19 restrictions were imposed. We could only complete the three-day workshop with three participants, and the fourth participant was then recruited from standard 9 of a central board school as a lower-bound sample for our research. For the second study, again conducted as a Lego Mindstorm workshop, we recruited ten students from different engineering institutes in India, of which eight participated. The set of 12 participants was a mix of learners with some or low prior experience in robotics or related domains like computer science, electronics and mechanical engineering. Participants were given a certificate after completing the Lego Mindstorm Workshop. To ensure this did not become a confound for our study being conducted as a workshop, on the first day, the participants were told that they just had to attend the three sessions (three days) to get the certificate and their performance or completion of the tasks would not have any consequences for it. A certificate could have been the motivation to get them to register for the workshop. Still, as mentioned above, the clarification ensured that it would not impact their thought or actions to solve problems during the study (workshop).

To address our two-fold research objective, we needed multiple data sources and a variety of analyses. We use video data to understand the participants' interactions with the resources. Observation logs were used to mark episodes of interest or log questions for the interviews. Semi-structured interviews were conducted to analyse the participants' perceptions and triangulate observations made by the researchers. The details of the participants, apparatus, data collection techniques, and analysis have been explained in Chapter 5 for Study 1 in Chapter 6 for Study 2.

3.6 Ethical Considerations

Deciding constraints on the research: As the research studies involved undergraduate learners from engineering colleges, it was essential to synchronise the research studies with their availability. The participants were asked to acquire the necessary permissions and consent from the concerned college/institution authorities for participation in research studies. The studies were conducted in the study and observation room setup of the Interdisciplinary Program in Educational Technology Lab at the Indian Institute of Technology Bombay, India, where all the observers used the observation room. In contrast, the participant and the mentor were in the study room. Student participation was voluntary; they were provided a meal each day and a (workshop) participation certificate for attending the sessions.

Consideration of ethical issues: Prior approval was obtained from the institutional review board (IRB) before conducting the studies with students. Additionally, detailed recommendations were designed for ethical consideration as human subjects were involved in the research studies (Cohen et al., 2013). These guidelines mainly include the following:

Preparation of procedures and documentation to obtain informed consent from the participants: A consent form was given to the participants before each research study. They were well-informed about the study's aim and method. The researchers gave them an explanation if they had any questions. After updating them with the complete information, the participants were asked about their decision to participate in the study. They were permitted at any point in time to discontinue participation in the research. Neither the primary researcher nor the supervisors of the researchers were involved in the grading of students who participated in the studies. Additionally, all participants were told that participation in the study would not affect their grades and academic performance.

Maintaining anonymity and privacy of participants: The anonymity of all the participants was maintained throughout, and all the data was collected, pre-processed, and preserved for this accordingly. Consent information provided to the learner about interviews is shown in the Appendix.

Permission for publication: Participants were asked for the necessary permissions for publication.

3.7 Summary

In this chapter, we argued for our choice of DBR as an overarching research methodology as it allows the refinement of problems, solutions, methods, and design principles in line with our research objectives. We also identified the specifics of the DBR iterations (DBR1 and DBR2) conducted in this thesis. We also identified the experiments carried out as part of these iterations and their study methods. Chapters 4 and 5 expand on DBR1, while Chapter 6 focuses on DBR2. The next chapter explains the DBR1 problem analysis process, including designing our learning environment's first version, Tinkery 1.0.

Chapter 4

DBR1: Problem Analysis & Design of Tinkery 1.0

In this chapter, we develop a deeper understanding of tinkering from experts from the perspective of a practitioner and an instructor. Then we discuss a few explorations of tinkering in the physical space and the role of a mentor. Based on our reflections and literature discussed earlier, we present the theoretical basis for our learning environment and how we designed the various features of our learning environment, Tinkery 1.0. We conclude this chapter by presenting the conjecture map of Tinkery 1.0 and discussing the design conjectures.

4.1 Expert's Voices on Tinkering from the Field

This exploratory analysis aims to understand tinkering from those who associate with and have been known to tinker. We will refer to them as experts. In the search for such experts, I came across a set of Massive Open Online Courses (MOOCs) by The Tinkering Studio at the Exploratorium, San Francisco, CA, USA, offered on Coursera. The MOOCs were named Tinkering Fundamentals: Circuits and Tinkering Fundamentals: Motion and mechanics. The objective of the courses is to enable and encourage teachers of STEAM to experience a tinkering approach and aid its adaptation to conceptual learning. The four-week course included two interviews/monologues every week. Here the experts talk about their ideas of tinkering and how they could be used to teach in STEAM. Table 4.1 describes the number of videos taken from the specific courses and their links.

Table 4.1: Video sources used for expert data analysis.

Coursera Course Name	Videos	Experts	Link
Tinkering Fundamentals: Motion and Mechanics	8	7	https://www.coursera.org/learn/tinkering-motion-mechanisms
Tinkering Fundamentals: Circuits	7	6	https://www.coursera.org/learn/tinkering-circuits

The transcriptions made available with the videos from the interviews of 13 experts (Bernie Zubrowski, Arthur Ganson, Eleanor Duckworth, Hubert Dyasiand, Carlos Zarpata, Shih Chieh (CJ) Huang, Rob Semper, Edith Ackermann, Jie Qi, Mike Eisenberg, Eric Rosenbaum, Gever Tulley and Mitch Resnick) were taken. These videos were classified as "inspirations", where the experts talk about their perspective on tinkering, and "pedagogical perspectives", where the experts talk about their recommendations for teaching and learning with tinkering. From a set of 15 videos, as shown in Table 4.1, of avg 8 minutes in length, around 100 excerpts were taken. Further, based on the relevance of tinkering-based activities, 79 were interpreted using a tinkerer's perspectives on the environment, attitude, materials, states and actions (Harris et al., 2016). We classified the interpretations among the environment, materials, states (of the tinkerer), actions and attitude as presented in Table 4.2. From these interpretations, implications were drawn from the perspective of a practitioner of tinkering (based on the inspiration videos) and an instructor's perspective (based on the pedagogical perspectives videos), which have been discussed below.

Table 4.2: Classification of interpretations from pedagogical perspectives.

Environment	**Attitude**	**Materials**	**States**	**Actions**
Partial-Manipulable	challenge as an opportunity/curiosity	Tinkerable tools	Task Switch / Context Switch / View switch	Encourage tangible action
Objects as memory	Mistake as an opportunity/curiosity	Design for personalised inquiry of phenomena and encourage it.	Identify, trigger Moreover, reassure actions that switch perspective	Encourage personalised actions (Play) to nurture creative processes
Opportunities for Building Dialogue	Play for possibilities, not just solution	Scaffold Exploration	Scaffold fluid movement between states	Reflection on Actions and its impact on Self-identity
Opportunities for Building experiences	Viewing from multiple angles for multiple mental perspectives	Encourage experimental play (intentional/unintentional)		Advantages of systematic deconstruction

Building risk and fool-tolerant environments.	Scaffolds and monitoring to Encourage a focus on interactions.			Insights from Reuse
	Lead to an inquiry from curiosity.			
	Target conceptualisation than a concept			

4.1.1 The Practitioners' Perspective

The practitioners in the videos talk from various perspectives based on their experience in making and problem-solving. These broadly classified ideas can be thought of regarding the physical aspects of tinkering and their personality traits.

> *"...and then there's something as a result of, there's an object that comes out of this process of interacting with the physical world."*
>
> \- *Arthur Ganson*
>
> *"It is going to allow you to, to work with materials that you were not thinking about, it is about bricolage, it is about hands-on, whatever you like."*
>
> \- *Edith Ackermann*
>
> *"It is a dialogue with the materials, rather than starting with a concept and trying to find something that illustrates that concept."*
>
> \- *Bernie Zubrowski*

Physical Aspects: Many practitioners mention bringing their ideas into the physical space by making them tangible. These tangible ideas allow them to address their curiosity with the ideas by interacting with them in the physical space.

The physicality of the environment is further exploited by keeping their tangible ideas (sketches, proof of concepts) or projects, irrespective of completion, in a visible space, often making mechanisms visible. In addition, they say these environments have emerged to be risk tolerant and, in some cases, risk-free. These aspects of the physicality of the environment allow them to think and work on problems continuously or become a reason just to keep themselves busy and engaged by experimenting with the materials and their constructions.

The physicality of the material around has been referred to as inviting curiosity, allowing them to create a dialogue. This dialogue consists of asking questions about the materials and observing the behaviour as a response when working with it. They refer to such dialogues as experiences, which they have a repository. This repository allows them to determine the affordances of materials, gauge their capabilities for achieving a desired objective, and get a sense of their heading when looking for a solution.

Personality Traits: The practitioners talk about their perspectives on their process of solving problems based on their actions, the various states they are in, how they transition between these states and their attitude or, in some cases, their dispositions.

Their attitude of setting self-goals makes inquiry and experimentation personalised. The goals could vary between understanding a phenomenon or evaluating ideas. Personalisation comes from self-parameterising goals by asking what they want to know and working until achieving a self-set target. The target could be form, function, behaviour or response. These targets allow them to keep focus and monitor interactions with material and environment, contributing to their creative process. This personalised process of inquiry targets conceptualisation as a means to derive knowledge, and the personalised process of experimentation helps build experiences when playing with one's ideas. This personalised process has also been considered to contribute to their identity as creators. In this inquiry and experimental pay process, they transition between numerous physical and mental states.

They talk about always being in a flow state with a realisation that alternates are always possible. Mistakes rather than hindrances have been considered as alternate realities that allow the possibility for alternatives for a different set of conditions. Hence they believe mistakes contribute to expanding one's knowledge and experiences, which they refer to as “problems that trigger thinking”. Alternates can also be seen as possibilities that are yet to reveal themselves. One needs to switch perspectives by switching tasks or performing actions to get an alternate perspective. A seamless switch between playful exploration and methodological deconstructions is a talked-about way that allows switching perspectives. Most of them have also talked about the variation in physical and mental states where they might seem to perform abstract actions in the physical state but are mentally in a different place.

Building on physicality, they talk about actions in physical space done with one's hands. We will refer to them as tangible actions. Continuing on the idea of physicality, they also talk about ideas of being present in the physical space, which is representative of their current understanding of the idea. We will refer to them as tangible ideas. Tangible actions with tangible ideas allow the discovery of influencing variables and aid in their reduction in finding the key variables. A method that leverages this tangibility of ideas and expressions is called systematic deconstruction, where one deconstructs a physical entity laying it out in a way to be able to explain their understanding of its form, function or behaviour. Tangible actions are said to trigger curiosity by raising questions that allow them to switch perspectives (physical and mental). The inquiry that follows such curiosity is motivated as a personal enquiry, given that it comes from one's actions on one's ideas.

To summarise, practitioners recommend:

- Building their ideas into the physical space by making them tangible.
- Keeping tangible ideas (sketches, proof of concepts) or projects, irrespective of completion, in a visible space, often making mechanisms visible.
- Asking questions about the materials and observing the behaviour as a response when working with it.
- Set self-goals to personalise inquiry and experimentation through self-parameterisation.
- Realise that there is always a possibility of alternates as mistakes can be considered as alternate realities that allow the possibility for alternatives for a different set of conditions
- Perform tangible actions (actions physically performed) with tangible ideas (physical artefacts)

4.1.2 The Instructors’ Perspective

While the practitioners' perspective focuses on their aspects of tinkering, instructors also view how one can nurture such aspects or use them to aid the learning processes for various age groups in STEAM. To maintain continuity from the practitioner’s perspective, we have broadly classified the recommendations regarding physical aspects of tinkering and personality traits that need scaffolding and nurturing.

"I always felt that you wanted to start students with a phenomenon and have them play around and investigate the phenomena to arrive at a conceptualisation."

- *Bernie Zubrowski,*

"The issue in science inquiry is what do you do to get an answer to that question. Do you ask someone who you think might know? Do you go to a book? Or do you actually look for the answer in the phenomenon you're talking about. I think the first impulse is to ask the material itself. We want an accurate answer. So, where can we get an accurate answer? We'll get an accurate answer by asking about the phenomenon itself."

- *Hubert Dyasi*

"My use of the term wonderful idea was how it feels to the person who has it, rather than how it is judged by somebody else."

- *Eleanor Duckworth*

Physical Aspects:

Given the importance of physicality mentioned earlier, there has been much emphasis on having physical objects available nearby to choose from. In addition, resources such as partially built solutions and partial-manipulable that allow interactions to discover their characteristics are helpful. These resources can be associated with initial ideas and used as environmental memory. To allow learners to take advantage of physicality, one must provide opportunities for them to build a dialogue with the environment, its resources and one's ideas. To enable such dialogues, one must scaffold students' exploration of the environment so that they build knowledge of the resources and use these experiences with their ideas. One must provide a risk-tolerant environment to ensure a smooth and free dialogue (exploration and experimentation).

The materials available in the environment should encourage and allow dialogue by providing immediate feedback, fluid experimentation, and open exploration. The tasks in the environment should be designed to exploit the material allowing personalised inquiry into ideas and phenomena. Along with these characteristics in the environment, one must also provide scaffolds for exploration and encourage experimental play, intentional or unintentional.

Personality Traits:

The instructor's perspective provides an insight into some crucial aspects of their actions, the various states and means of transitioning between them and developing certain attitudes. These factors are important as they influence the processes of solving problems.

The most frequently discussed aspect in developing an attitude is for the tinkerers to realise that mistakes are just alternate realities and that the way to understand them would be to look at them as opportunities. These can be used to develop curiosity towards why things behave differently than intended, rather than as a negative state, similarly looking at challenges as points of opportunity and curiosity. To channelise such curiosity into inquiry, it is recommended that opportunities be provided for experimental play towards possibilities and not just as solutions to problems.

Another important aspect of experimental play is developing the ability to focus on interactions between the environment, materials and a learner's ideas and observing the impacts of these interactions on either the environment and materials or one's ideas or both. Scaffolds in activity design or from the mentor as prompts could assist learners in developing focus on such interactions. The other aspect of focused observation of interaction is visually viewing the same from multiple angles to trigger multiple mental perspectives. Such changes in perspectives or mental states are a way of accepting mistakes and challenges as alternate realities.

Switching states (mental and physical) have been said to have significance, like fluidly moving between playful exploration and systematic deconstruction. This can be done by switching perspectives. The perspective switch has been credited to changes in the task, changes in context, or even changing the view visually. For learners, it is vital to be able to switch hence the environment, and the mentors should scaffold learners to identify opportunities to switch perspectives using triggers and reassurance on the actions, which in turn will allow them to switch states.

The physicality of actions is essential to practitioners, which is the same when we look from the instructor’s perspective. Practitioners emphasise hands-on activities as they act as a gateway or a conversation starter with the material one is to work with and the environment one works in. Hence the materials and the environment should provide and even encourage hands-on actions. A few ways of encouraging such actions have been discussed as scaffolding for systematic deconstruction or opportunities for reuse. These actions can be either free exploratory, which could be encouraged by motivating personalisation by inquiring about one's questions and

Self-parameterisation of expected outcomes. The actions could also be motivated by an external goal or requirement, which can be scaffolded by encouraging reflection in action and reflection on action and associating them with the outcomes. Intermittent reflection has also been said to be essential for nurturing one's creative process and developing one's identity as a creator.

To summarise, instructors recommend:

- Keeping resources such as partially built solutions that allow interactions to discover their functional or structural characteristics.
- Provide opportunities for them to build a dialogue with the environment, its resources and one's ideas by scaffolding exploration.
- The environment should encourage dialogue by providing immediate feedback, fluid experimentation, and open exploration.
- Scaffolds to develop curiosity towards why things are behaving differently than intended.
- Opportunities are provided for experimental play towards possibilities and not just as solutions to problems.
- Scaffold’s ability to focus on interactions between the environment, materials and a learner's ideas and observe these interactions’ impacts.
- Mentors should scaffold learners to identify opportunities to switch perspectives, allowing them to switch states.
- Ensure materials and the environment provide and even encourage hands-on actions.

4.2 Exploration of Tinkering in physical space

After understating experts’ perspectives and processes, we aimed to explore aspects of tinkering in a physical space. Our initial open explorations were focused on getting know-how of existing tinkering kits and experience working with these kits. We gathered information on several kits and narrowed it down to two for further exploration based on their variety, availability and popularity. We explored a locally available kit from Next Robotics Kit (iPitara) (*Next Robotics*, n.d.) and the Lego Mindstorms EV3 (Ringwood et al., 2005). We had also considered gathering our open-ended kits, like an Arduino, Raspberry Pi and some electronic components. However, such components had many challenges regarding compatibility and ease of use. Once we finalised the kit based on its alignment to tinkerability, we used it to conduct a small engineering design workshop to conduct a contextual inquiry on the role of a mentor when solving problems with such kits. The mentor participated in the workshop by scaffolding students' problem-solving process, providing operational & procedural information, triggering reflections through questions, and nudging students towards best practices.

4.2.1 Role of Resources

Our initial exploration was with the iPitara kit, which looks more like the Mechanix kits consisting of plates and beams as perforated metal strips and nuts and bolts to make connections. In addition, they had wheels, some motors, sensors, remotes and a brick (microcontroller) based on the older Lego NXT controller. The kit came with a drag-and-drop-like programming environment called the Think Next (an extension of the LabView platform) and some digital manuals. We followed the manual and built models with the kits to experience the behaviour of the resources and their capabilities. Our initial experience was that the Mechanix components lacked freedom in mounting the electronic components when trying some custom builds, and this could be as Mechanix, on its own, is a complete building kit, and the electronics have been designed to accommodate a connectivity mechanism. The kit is not designed with all the components as a whole. Secondly, the software available was a key-based proprietary software which required installation by a professional and limited the number of systems it could use.

The second kit we explored was the LEGO Mindstorms EV3 Kit (Education + Expansion Set). The Lego kit is built on the principles of tinkerability (Resnick, 2017). During our initial explorations around 2017, we also used a lab view-based programming environment which was changed to a scratch-based environment in 2019 before we did our studies. The scratch-based environment better fits the requirements of tinkerability in terms of ease of access and freedom to explore and arrangement of the control blocks. The kit provides enough resources, and during our explorations, we realised it allowed customisation. We built a wide variety of toy bots and, later, some functional bots, including a cart robot capable of carrying a camera, bottles, food containers, etc. This kit has also been used in many studies on tinkering and making in the literature (Lego, 2019; Ringwood et al., 2005). Hence, we choose to use Lego Mindstorms as an off-the-shelf tinkerable kit as the resource for our tinkering environment. Our approach to interacting with Lego started with building a highly complex model from the manual, discovering the affordances of the various pieces, and then building models that we were fascinated with, including a bot to carry things resulting from solving a problem. As an extension of our exploration, we also gave the kit to others who were new to the kit. We observed that the way to go was selecting one or more models from the manual and building on them. This developed our confidence in using the Lego Mindstorms Kit as a resource to solve problems. However, we understood many other things like the problems, the arrangement of resources, the need for scaffolds and the role of the mentor, which had to be brought together through a pedagogy for such an environment.

4.2.2 Role of Mentor

To understand the role of a mentor, we conducted a contextual inquiry (Beyer & Holtzblatt, 1998) in a young engineers workshop with five middle school children who had similar exposure to the LEGO Mindstorm robotics kit. The workshop started with a hands-on introduction session. The second part of the workshop was a challenge to create a dirt-cleaning robot using a LEGO Mindstorm robotics kit and other materials like cardboard, sponge blocks, and paper cups in two hours. Fig. 4.1 shows a robot built as a solution to this challenge. All the components used for the robot had a cost associated with them which had to be minimised. The participants were divided into two teams with the same material set for each group. Both the teams had received a worksheet with standard step-by-step engineering design instructions and probes for good practices of tinkering, along with an information manual for the components of Mindstorm. Group one had two participants and was assigned a Mentor Companion (MC). MC had to provide triggers in the form of probes and information about the components of LEGO Mindstorm whenever asked by the participants in a seamless conversational manner. The entire study was recorded, and the videos were transcribed. The transcriptions were analysed and categorised through the lens of seamless interactions. From this analysis, two themes emerged: 1) Just-in-time information (JITI) from the MC that enabled the participants to use the components of the kit and 2) Just-in-time tinkering triggers (JIT3) from the MC to encourage them to try and experiment. We also compared the presence and absence of MC on the above themes.

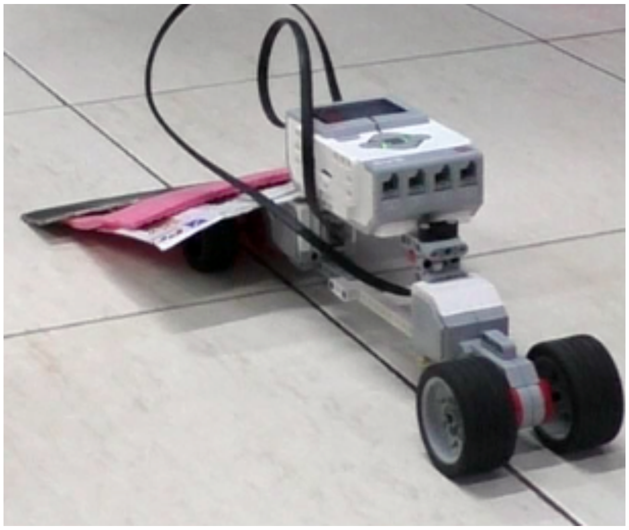
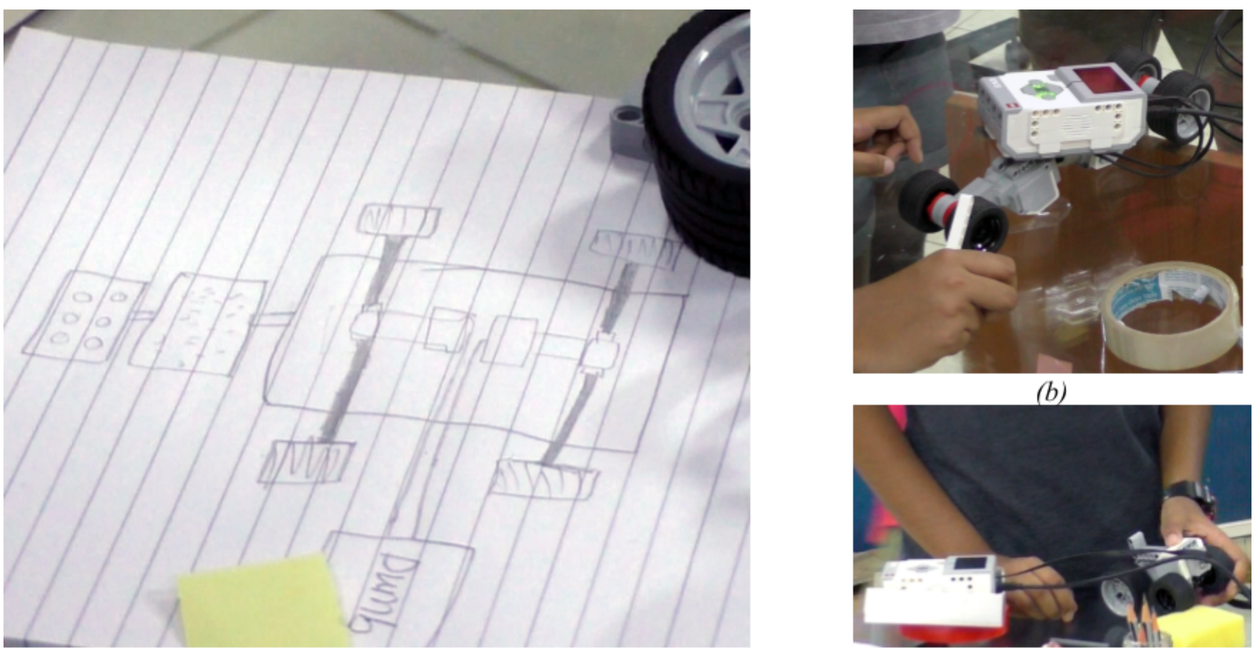


Figure 4.1: A four-wheel cleaning robot designed by group 1.

Figure 4.2: An intermediate design by group 1 with two wheels and a single motor.

Just-in-time tinkering triggers: When MC provided just-in-time triggers, the participants could differentiate and prioritise the primary and secondary goals streamlining the problem-solving process. Moreover, they overcame their inhibitions of trying unknown components and later were seen experimenting with the affordances of the materials on their own to achieve the best possible result. We provide two instances. Participants of group one were prompted to ignore the cost of the robot and focus on making the robot. They then worked on two primary functions, locomotion, for which they built the robot, and cleaning, for which they built the mop. In the first cycle, their robot was a single two-wheel motor, but they needed clarification on a box to collect the dust and a sponge block to wipe the dust. The MC said, *"Why don't you try both?"*. They ruled out the box as it was weak to sustain the robot's weight. In contrast, the friction due to the sponge block inhibited the robot's movement, as seen in Fig. 4.2. The MC asked them to write their challenges on a note and keep it on the desk and later said: *"Could you change something from your previous approach that would help overcome the challenges?"*. The participants decided to use a four-wheel two-motor design by replicating the construction on the robot's other side, which was more stable and robust. They switched to a mop instead of the sponge block, which could be dragged behind the robot seen in Fig. 4.1. They kept experimenting with a different configuration of attaching the mop to clean most dust in one go.

Just-in-time information: When the MC provided information on the affordances of the kit's components and referred to the prefabricated solution using those components, participants were seen to tinker with the affordances for their solution idea. This in-time information about component affordances enabled them to derive their solution from the components available in the environment. Let us look at an example from the workshop. Group one participants began with a two-wheel motor to create a dirt-cleaning robot. They were trying to add the EV3 brick over it. Upon inquiring about the connectivity of the brick, the mentor companion responded by pointing to a set of slots on the EV3 brick, saying, “Can you think of a way you could use these?” and then referred to an activity they did use beams and frames in the workshop session which has similar slots. With this procedural information, they figured out how to mount the brick on the motor, as seen in the picture. Similarly, while programming the motor, they noticed the alphabet D written on the motor code block, to which they asked, “What is D in that block ?” the mentor companion responded by pointing out labels on the connection ports of the EV3 Brick. With this information, the participant could make the connection that this is how they could code the motor connected to D or any motor connected to any port.



(a) (b) (c)

Figure 4.3: Conceptual design made by group 2 a) not aligned with the available components. b) & c) inability to make connections between the motor and the brick.

Presence and absence of MC: Seamless availability of information from the MC in group 1 encouraged the participants to tinker with different kit components. However, the difficulty of obtaining such information during ideation discouraged the usage of new components in group 2. Secondly, triggers guided participants in managing complexity by helping them make decisions and encouraging them to tinker with the available components. In contrast, participants kept switching between different functions and requirements in their absence while coming up with a conceptual design of the solution that was not aligned with the components available. Let us look at some examples; Group two made a conceptual sketch considering just the motors and the EV3 brick, as seen in Fig. 4.3a, constantly trying to keep the cost low hence failing to realise the robot's structure. Later they used cardboard to create the structure and connect these components with a two-sided adhesive tape, as seen in Fig. 4.3b. They kept discussing their conceptual design, to which they were fixated and worried about the cost. Eventually, they failed to finish the challenge in the given time. On enquiring about the reason for not using the beams and frames, they said, *"We would have to create a container using many beams and mount it on the motors to place the EV3 brick in it, and that would cost a lot."* They were unaware of the function of slots on the EV3 brick. When asked about the worksheet, the groups said, *"We were too busy working on the robot, so we did not get time to fill the worksheet".*

Through this exploration, we concluded that tinkering is favoured when there is seamless availability of information and just-in-time triggers through a mentor. We also understood the various roles of a mentor to be a non-contributing participant and let the participant have agency on the solution and the problem-solving process. That could be done by scaffolding participants with operational information, reflective questions and prompts. As mentioned by Mitch Resnick, "*Good teachers and good mentors move fluidly among the roles of catalyst, consultant, connector, and collaborator*" (Resnick & Robinson, 2017). Through this exploration, we identified the mentor actions that allowed them to switch between such roles.

4.2.3 Summary and Reflections

Experts discussed important aspects of tinkering as practitioners, which also have implications for instructors. These physical aspects impact tinkering, like the materials' characteristics and the space's contents and arrangement. Alternatively, in terms of the personality traits that one would observe in a tinkerer, like their attitude towards problems, materials etc. Their comfort and acceptability towards transitions between states when solving problems and their actions physically in the space.

A key point that emerges is the importance of physicality, be it resources, actions or even their ideas which they make tangible by building them in the physical space. This physicality brings several iterations of exploration and plays with materials and ideas in the problem's context. This helps evolve their solution, allowing them to build a dialogue among the materials and their ideas to eventually build a better understanding of the problem, a domain or a small curiosity-driven project. The other important aspect is the tinkerer himself/herself: their ideas (agency), traits like curiosity, persistence and ability to reflect and switch perspectives while being engaged in the subject matter.

Our explorations of tinkering kits established that along with the physical traits of the materials, it is crucial to keep the agency with the learners while scaffolding their journey and using mentor intervention as a scaffold and not as a means of instruction. With these reflections, we will discuss the theoretical basis of our learning environment and how we used it to design the first version of Tinkery.

4.3 Designing for Nurturing Tinkering

4.3.1 Theoretical basis

We looked at several models from the literature on creativity and making, such as creative learning spiral (CLS), think make improve (TMI) and spark sustain deepen (SSD). CLS sequentially transitions between five phases in an upward-moving spiral based on the actions and activities. TMI and SSD have three stages, where the stage determines the activity focus. Both these models work well in the case of learning from tinkering but do not explicitly emphasise problem-solving the way we define tinkering. Hence, we adapted from the three-stage models TMI and SSD and determined three primary focus points for tinkering for problem-solving: exploration, experimental play (or solving in terms of problem-solving) and evolution. We define them as the focal point of the activities over time.

We have drawn from research in multiple disciplines, such as the learning sciences, engineering design and creativity, discussing various tinkering aspects. Key theoretical concepts from these disciplines have formed the basis of our design. In addition, the reflections emerging from the analysis of expert practitioners and instructors (Sec 4.1) have been incorporated. Our learning environment has been designed with mechanisms that scaffold exploration, encourage play, provide contextualisation, allow progressive formalisation, and encourage an evolutionary mindset.

Scaffold exploration: Exploration has been discussed by experts (Section 4.1) as the means of discovering a solution by discovering the context in which the problem is situated and the affordances of the resources available to solve the problem. For it to happen when a problem is given to be solved in the physical space with physical resources, one would require support for exploration (Resnick & Robinson, 2017, p. 112) (Louridas, 1999) (Honey & Kanter, 2013). Scaffolding is one-way mentors who support students through specific methods as they develop a concept or skill. Scaffolding can be done by structuring complex tasks, using representations that the learners can inspect to reveal important information, organising tools and artefacts per semantics and embedding expert guidance (Quintana et al., 2005). Scaffolds can be generated by having an ordered set of problems, having objects made of building material that participants can investigate, arranging the resources in the physical space and with mentor intervention.

***Encourage Play*:** Play (experimental play) has been considered an experimental, iterative style of engagement in which people are continually reassessing their goals, exploring new paths, and imagining new possibilities. (Honey & Kanter, 2013). Similarly, play or playfulness is central to creativity (Resnick, 2007), where it is the means of getting to know the possibilities of the environment. This was also seen in the expert's perspective, where they discuss play with the perspective of possibilities rather than the solution. Literature on play explicitly mentions using material and phenomena that provide immediate feedback; multiple possibilities and pathways towards a solution; and opportunities to complexify thinking over time (Honey & Kanter, 2013; Smith & Roopnarine, 2018).

***Provide Contextualisation*:** Situating the learning in the context (Brown et al., 1989) can be done by providing anchored instruction (Bransford et al., 1990) and some aspects of cognitive apprenticeship (Collins et al., 1986; Lave & Wenger, 1991). Anchored instruction talks about problems as questions related to a story or narrative that presents a realistic (but fictional) situation with extensive and diverse opportunities to explore the problem and allow learners to discover subgoals in solving the problem. Cognitive apprenticeship also talks about providing a just-in-time scaffold for modelling expert behaviour, encouraging reflection and making the learners describe their thoughts as they solve the problems. This was also seen in the expert's perspective, where they discussed situating the exploration and play within the subject matter. Similarly, literature on tinkering discusses the consistency of problem and project-based learning with real tools, materials and real problems as the driver of curiosity (Resnick & Robinson, 2017). Tinkering literature emphasises make-believe play while they engage in disciplinary practices like defining problems, modelling, investigation, analysis and argumentation which scientists and engineers use to develop new understandings of materials and phenomena (Petrich et al., 2013).

Progressively Formalise**:** Education literature suggests starting with the informal ideas that the learner brings, and then teachers and mentors work to formalise them progressively. The objective is to allow them to build on their informal ideas in a gradual but structured manner to acquire the concepts and procedures of a discipline (National Research Council et al., 2000). In theories of situated learning and Legitimate Peripheral Participation (Lave & Wenger, 1991), the novices start with low-stakes productive tasks. They become aware of the community's tasks, vocabulary and organising principles through them. This was also seen in the expert's perspective, where they talked about the complexity of problems and the mentors' actions. Along similar lines, making literature talks about the need for the development of educational contexts that link the practice of making and tinkering with concepts and theory to support discovery and exploration by introducing new tools that range from basic to advanced levels and design opportunities for new ways of thinking about building, making with problem-solving (Dougherty, 2013).

Encourage Evolutionary Mindset**:** Research suggests curiosity may initially be fueled by a practical need to develop understanding in an area to advance into disciplinary practices or just complete a project. However, this leads to an ongoing curiosity and wonder about the world and the phenomena we encounter daily (Regalla, 2016). Researchers recommend ensuring freedom to pursue curiosity to nurture creativity (Resnick & Robinson, 2017). To ensure freedom to pursue or foster curiosity, the literature on tinkering suggests providing opportunities for undirected play, adequate self-exploration, and encouraging questioning and experimentation (Honey & Kanter, 2013; Petrich et al., 2013; Resnick & Robinson, 2017). This aspect was also seen in the expert's perspective, emphasising evolving learners' ideas with curiosity.

4.3.2 Proposing “Xpresev”: Explore, Solve, Evolve

To tinker for problem-solving, especially in engineering design, there are only a few best practices with borrowed pedagogies. There is a need for a pedagogy that focuses on the learning aspects of exploration and play and the evolution of the ideas essential for problem-solving. Hence, from the theoretical basis stated above and our literature synthesis, we understand that tinkering is driven by exploration and experimental play leading to progression, be it the completion of a project or learning a disciplinary practice. In the literature review section, we defined tinkering as evolving a solution by building experiences of exploration and play, i.e. tinkering involves exploration and playing with resources at hand to build experiences and use those experiences to develop solutions to the given problem. Hence to design a learning environment for tinkering-based problem solving, we had to focus on each of these aspects of tinkering while keeping in mind that these activities happen in tandem. The essential aspects of tinkering to solve problems are: *exploring* what we have and what we want to do, *solving,* which is the play between what we want to do with the things that we have and the things are capable of, and finally, reflecting and *evolving* the solution at hand either with better ideas or new or new ways of using resources. Hence the pedagogy must ensure that these aspects of exploration, solving and evolution happen, but at the same time, the learners should be allowed to do them in any sequence and any manner they want to. The pedagogy can sequence learners to allow the structuring of activities that may primarily focus on one of the three aspects but allow them to do any of the three at any given time. One crucial thing the pedagogy must ensure is the opportunity for the learners to reflect as and when they do each. The objectives of the pedagogy in detail are: -

Explore: The features of free exploration to capture intrinsic motivation have been incorporated in the explore phase. Learners start with minor problems, which require them to interact with the physical space using the components available in the surroundings to solve the given problem. The emphasis is on asking the learners, “What can the components/resources do?” and “What can I do to solve the problem ?”. This helps them know what resources “can do” and what they “want to do” to solve the problem.

Solve: Focuses on externalising a learner's idea by building it in the physical environment regarding available resources. This can be done by allowing the learners to start building solutions for small component problems by using the affordances of materials explored in the previous phase and using them to externalise their ideas. The emphasis is on getting the learners to ask, “What is it that the components/resources can do for me or what I want to do”. This creates mappings between the “can do” of the resources and their “want to do’s” for solving the problems.

Evolve: Get the learners to evolve their solutions ideas by managing complex requirements of a similar problem. To evolve, the learners are scaffolded to identify personalised objectives for solutions. Then to meet those objectives, they are triggered to discover emergent challenges and overcome them through iterations of exploration and play with the available resources and ideas. The emphasis is on getting the learners to ask, “Is there anything else that can also be done?” This could be the need to find an alternate mapping that works better for more experimental play or the need to know or test the possibilities of resources or one’s ideas further, hence more exploration.

The pedagogy has been operationalised in three phases. The challenges in Phase 1 are candidate sub-problems for the problems in Phases Two and Three. This is done by adhering to progressive formalisation. The Objectives determine the focus of problems designed for each phase and the activities to be performed by the mentor. Fig. 4.4 and Table 4.3 show a summary of the same.

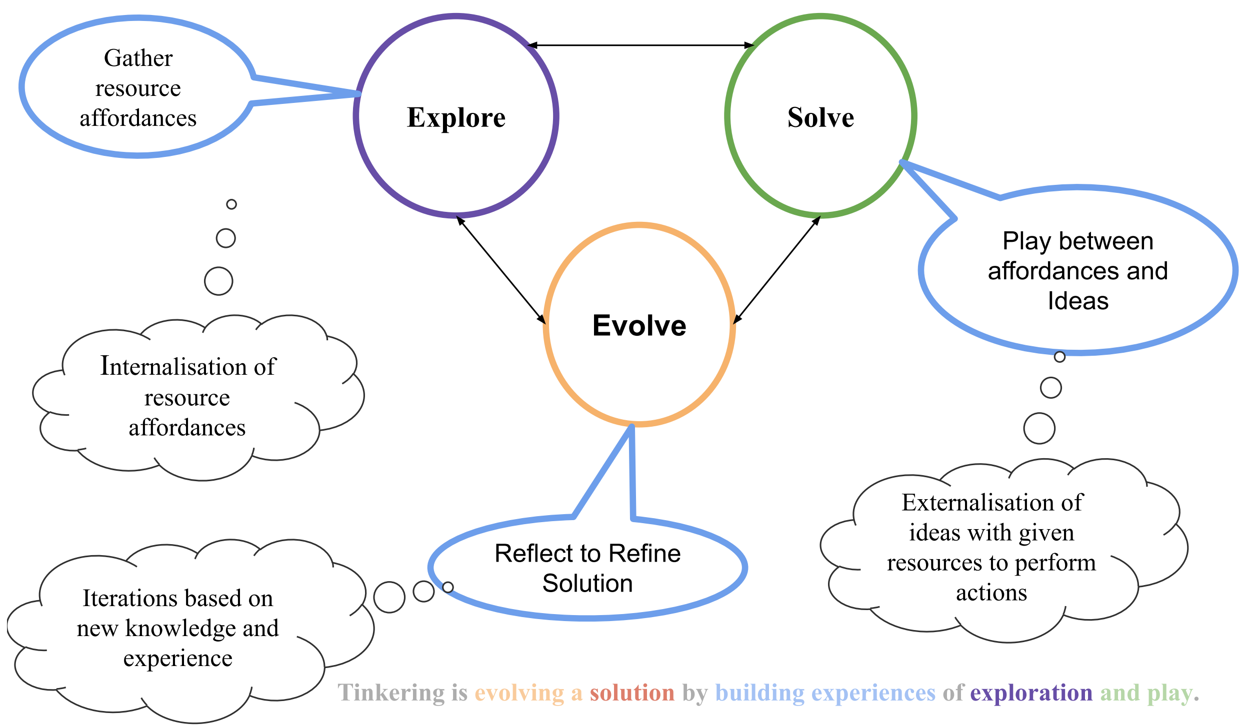


Figure 4.4: The various phases of the Xpresev pedagogy, the primary activities and their objectives

Table 4.3. Operationalisation of the Xpresev pedagogy into three phases.

Phases	Objectives	Activity Focus	Learner Goals
1	Explore	Explore resource affordance and use them to solve candidate problems	Understand and use resources based on their affordances and determine the affordances required for their solution approach.
2	Solve	Solve problems by finding solutions for sub problems with the given resources.	Divide a problem into subproblems & identify required affordances. Use resources based on required affordances OR solve sub problems based on the affordances of the resources available.
3	Evolve	Improve the solution to address new or emergent challenges.	Reflect on previous knowledge and experiences Improve the solution by iterating with alternate possibilities, resources and affordances

4.3.3 Designing Tinkery 1.0 - A nursery to nurture tinkering

> *"It needs to be nurtured, encouraged, supported. The process is like that of a farmer or gardener taking care of plants by creating an environment in which the plants will flourish."*
>
> \- *Mitchel Resnick* in *Lifelong Kindergarten,*

The key elements of our learning environment include robotics-based problems, expressive pedagogy, scaffolds, Lego as resources and a mentor, the critical elements of our learning environment. We designed the learning environment for problem-solving vehicular robotics with the essence of nurturing tinkering. Hence, we named it "Tinkery", similar to the word "nursery", which has a similar connotation of nurturing plants.

Tinkery Problems: The problems are based on the Lego Mindstorms kit. Learners are initially given challenges that nudge them to explore the affordances of the components available in the kit. The challenges require them to use a particular affordance of the resource offered in the kit to explore the possibilities of what the resources can do. The next problem is based on the challenges given initially. Finally, the learners try to refine the solution to the problem or attempt a problem of their choosing.

The problems in Tinkery are engineering design problems designed to progressively complicate yet allow the learners to connect their understanding from one problem to the next through conceptual similarity allowing the use of resources that they initially explore yet providing the opportunities to explore and use more new resources. This aligned with progressive formalisation with the available resources and materials. The problems that start as challenges require a specific affordance of certain resources and then gradually complicate the search for affordances required which provide an overall structure to exploration hence also acting as a scaffold for explorations. The problems subscribe to low floors, high ceilings and wide walls with open-ended challenges and physical, observable yet broad solution requirements that allow a choice of personal pathways to solve problems. This ensures the problems encourage play.

Further, in alignment with contextualisation via situated learning, the problems are based on the physical space's characteristics, like the room's volume or the arrangement of specific objects in the room or on the floor. The initial challenges by design act as possible subproblems for the problems given in the later stages. The solution objectives of the problems gradually broaden and vary with an increase in complexity by increasing the number of key variables to manage or the concepts to choose from. Fig. 4.5 shows the various challenges and the problems and the variation in their complexity based on the number of decision variables and the components required.

Tinkery Resources: The Lego Mindstorms kit is designed with the principles of tinkerability, allowing immediate feedback, fluid experimentation and open explorations(Petrich et al., 2013). The kit also supports tinkering ability by allowing learners to focus on solving by providing enough opportunities and tools like serial monitors and motor controllers for intermediate-level insights (Resnick & Robinson, 2017). Tinkerablity and tinkering ability together help scaffold exploration and encourage play. To help us focus on the other aspects of Tinkery, we choose to go with such an off-the-shelf solution as a part of resources. Moreover, by limiting the type of building resources, i.e The kit, we as researchers have been able to develop a thorough understanding of the resources and their affordances. This will help us interpret the learners' interactions with these resources.

C1*: Use the lego brick with any sensor deemed fit to measure the area and then the volume of the room you are in.* **- Ultrasonic vs IR sensor - Ultrasonic sensor max range**

C2*: "Use the lego brick with any sensor to sense a given set of color pieces and use them to program expressions on the lego brick screen"*. - **Color detection feature of reflective sensor, , programming environment, brick display, use serial monitor (port view)**

P1: "*Build a bot that should be able to go from a point A marked on the floor to another point B marked on the floor avoiding everything that is there on the floor using the control buttons on the brick or the app as a remote control or by building your own remote"*

C3*: Build a bot that can move forwards or backward.* **Beams, Frames, Pegs, Wheels, Axels, Motors**

P2: *"build a bot that can cross a bump like obstacle to reach an incline plane. Then climb the incline plane and reach the platform at the end of the incline plane."*

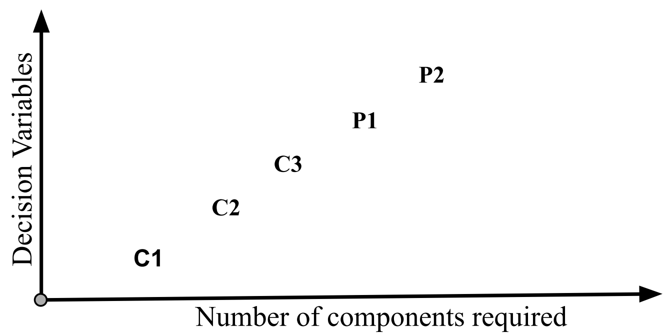


Figure 4.5: Challenges and problems given during study.

Tinkery Scaffolds: Keeping exploration and play in mind, scaffolds were designed for the problems by providing an implicit structure towards exploration. In alignment with our theoretical basis, we designed some partial-manipulable using components from Lego as scaffolds. These act as representations that learners can inspect to reveal important properties of these resources' underlying form, function and behaviour (Quintana et al., 2005). Another scaffold is related to the spatial arrangement of the resources. The space was divided to accommodate the display of the resources and have space for building. The table had a computer which housed the programming environment and an internet connection to allow learners to explore at will (Peppler et al., 2016a). Fig. 4.4 shows Tinkery 1.0, which comprises an ordered set of problems, Lego Mindstorms EV3 kits as building resources arranged as per Lego recommendations, the Xpresev pedagogy, scaffolds in the form a partial-manipulable and a mentor to initiate reflections and prompt learners when required.

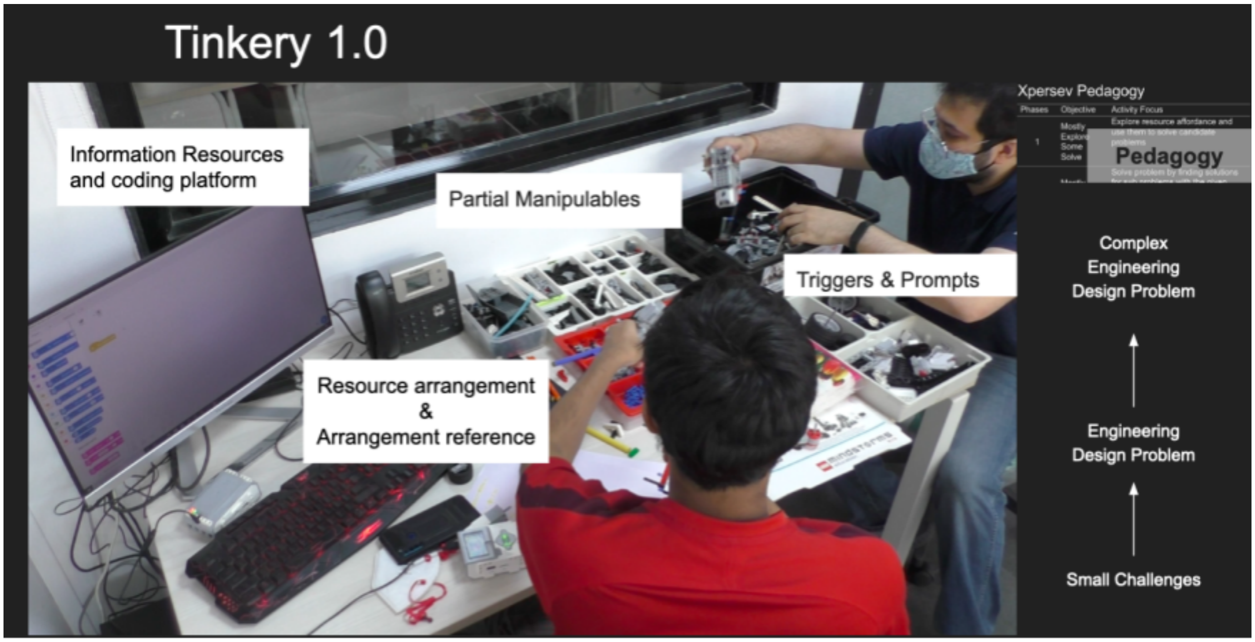


Figure 4.6 Overview of the learning environment tinkery in its version 1 with it components

Tinkery Mentor: The role of the mentor in Tinkery 1.0 and 2.0 is of a non-contributing participant as they are as involved in the problem-solving process but do not contribute ideas towards solving the problem. The mentor provides prompts and triggers to encourage or discourage a behaviour; hence, the mentor must be very well versed with the entire problem, which they must have solved and explored the variations. This is a means of embedding expert guidance to scaffold exploration (Quintana et al., 2005). It also helps mentors to empathise with the learners and scaffold them towards exploration and play in terms of can-do's and want-to-dos by posing questions encouraging play. Giving multiple possible approaches and leaving the trajectory to the learner is always recommended. The mentors could also intervene at various stages if they encounter learners in discomfort and scaffold them towards flow (Peppler et al., 2016b).

The mentor will foresee many challenges in the learner's trajectory, but they should not interrupt the learner unless the learner has hit the hurdle and asked for help. If the mentor does foresee failure, they could question the learner's approach but should allow the learner to observe failure. It is a crucial step to understand the resources and the solution approach (Honey & Kanter, 2013). This helps develop curiosity by allowing undirected play and providing adequate time for self-reflection leading to an evolutionary mindset. One preferred approach is to re-articulate the questions posed by the learners, which clarifies that the learner and the mentor are on the same page and acts as a trigger for reflection for the learner. Another approach in such a case for the mentor is to bring the learner to the point where many possibilities exist without explicitly mentioning them. Then question the learner to think about possibilities or give suggestions by using the resources to communicate, which aids curiosity through questions and experimentation.

Mentors, at times, make the learners talk about their problem-solving process as curious observers with the help of the resources they use, providing an opportunity for the learner to describe their thoughts and also as an aid to reflection (Collins et al., 1986). Further, mentors provide just-in-time operational/procedural information or point them toward sources where they could obtain such information. Similarly, mentors provided Just-in-time prompts to work things out in the physical space if the learner was stuck in thinking cycles. Mentors also provide prompts to be able to switch perspectives of thinking and also of viewing their current state to be able to obtain alternate perspectives or macro-micro views of the problem or their problem-solving approach. These prompts encourage learners to model expert behaviour (Lave & Wenger, 1991). We expanded the set of prompts further after our experience in DBR 1, which we will discuss in DBR2.

To summarise, Tinkery in it version 1, as shown in Fig. 4.4, comprises an ordered set of problems, Lego Mindstorms EV3 kits as building resources arranged as per Lego recommendations, the Xpresev pedagogy, scaffolds in the form of a partial-manipulable and a mentor to initiate reflections and prompt learners when required. To evaluate the design of Tinkery 1.0, we develop conjectures for these features and the processes they will aid. We discuss this further in detail in the next section.

4.3.4 Conjectures of Tinkery 1.0

We use conjecture mapping (Sandoval, 2014) to analyse the embodiments of Tinkery 1.0. Our high-level conjecture is that a learning environment for problem-solving in engineering design that scaffolds exploration encourages play, provides contextualisation, progressively formalises and encourages an evolutionary mindset encourages learners to tinker to solve problems. Fig. 4.5 shows a high-level conjecture map of Tinkery 1.0 for DBR cycle 1. The features of the environment (embodiments) that have evolved, as discussed in the above two sections, give rise to certain practices (mediating processes) that are known to be conducive to tinkering-based activities from expert insights and best practices.

DBR-1 focuses on the embodiments and the mediating processes by choosing only to evaluate the design conjectures (DC). Based on the conjecture map seen in Fig. 4.7, the board design conjectures for Tinkery and their detail are as follows.

- **DC1:** The presence of partial-manipulable encourages learners to engage in playful exploration and perform actions on built artefacts to seek feedback.
- **DC2:** Partial-manipulable assists learners in considering failed attempts as opportunities to try new creative approaches and develop workarounds.

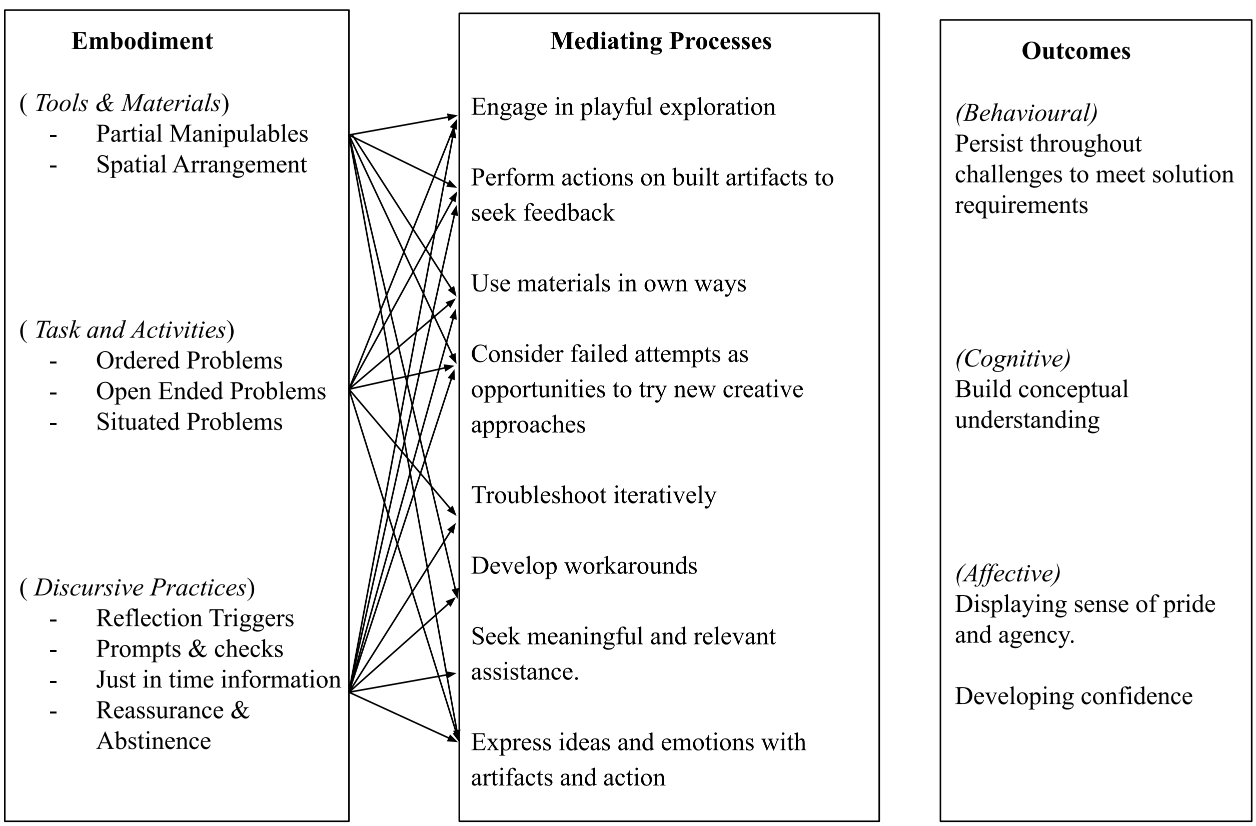


Figure 4.7 Conjecture map of Tinkery in DBR 1.

- **DC3:** Partial-manipulable helps learners to express their ideas and emotions with artefacts and actions.

- **DC4:** Access to resources displayed according to Lego reference cards supports learners in performing actions on built artefacts to seek feedback, using materials in their way and developing workarounds.
- **DC5:** A set of problems ordered based on complexity engages learners in playful exploration.
- **DC6:** Problems in the physical space allow learners to perform actions on built artefacts to seek feedback and troubleshoot iteratively.
- **DC7:** Open-ended design problems allow learners to use materials in their ways.
- **DC8:** Open-ended design problems allow learners to express ideas and emotions with artefacts and actions.
- **DC9:** Open-ended design problems help learners consider failed attempts as opportunities to try new creative approaches.

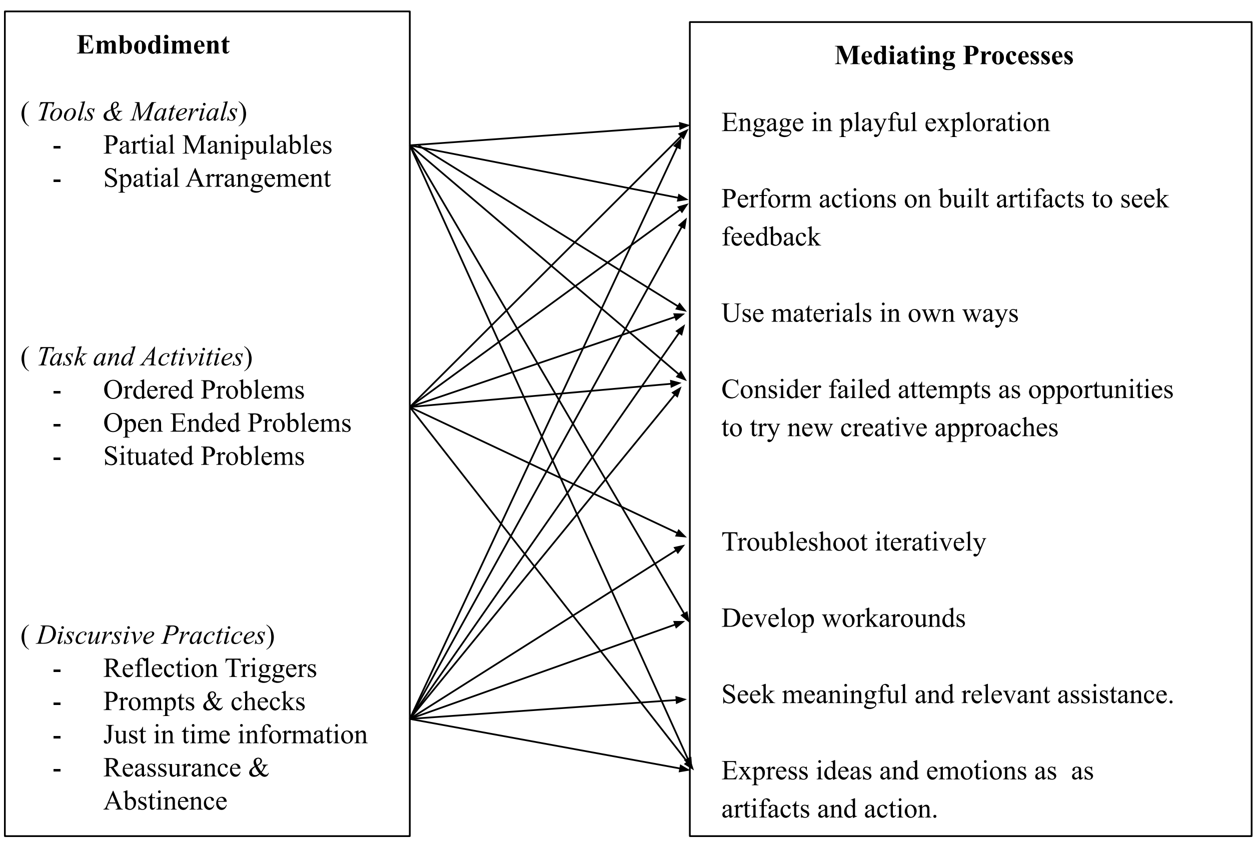


Figure 4.8 Design conjecture map of Tinkery evaluated in DBR 1.

- **DC10:** Reflections triggered with questions direct learners to engage in playful exploration and perform actions on built artefacts to seek feedback.
- **DC11:** Reflections triggered with analogies or questions help learners consider failed attempts as opportunities to try new creative approaches and develop workarounds.
- **DC12:** Prompts and checks from the mentor nudge learners to engage in playful exploration and perform actions on built artefacts to seek feedback.
- **DC13:** The availability of just-in-time operational information helps learners remain engaged in the playful exploration and seek meaningful and relevant assistance.
- **DC14:** Reassurances from mentors help learners consider failed attempts as opportunities to try new creative approaches.
- **DC15:** When mentors avoid prompting, they allow learners to use materials in their ways and express ideas and emotions with artefacts and actions.

The conjectures mentioned above are based on the design of the first version of Tinkery 1.0, where its features have been derived from the theoretical basis, and the mediating processes are based on experts' data, our explorations and the literature. To get a better understanding of what happens when learners tinker in Tinkery 1.0 and evaluate these design conjectures, we designed a study, and the findings gave us a richer insight not just into improving Tinkery 1.0 but also into the processes of a tinkerer’s design approach which we talk about in the next chapter.

Chapter 5

DBR1: Evaluation and Reflection of Tinkery 1.0

In this chapter, we present the evaluation of the design of our learning environment Tinkery 1.0, where we discuss the research questions, the study design, the procedure, the data sources and the analysis method. Then we present our findings from the study and close this chapter with implications for tinkering in problem-solving and improvements in the learning environment design for our next cycle of DBR.

5.1 Study Design: Evaluating the design of Tinkery 1.0

This study provides participants with three challenges followed by two design problems from robotics with Lego Mindstorms. The study was conducted in three sessions over three days. Participants solved problems in Tinkery 1.0 along with a mentor. Data collected were in the form of video observation logs, along with a post-session interview.

5.1.1 Research Question

One of the broad objectives of this thesis is to design a learning environment for nurturing tinkering for problem-solving in engineering design.

This study investigates if the designed features of Tinkery 1.0 work as specified in the design conjectures leading to a specific research question on *how the features and learning activities of Tinkery 1.0 support students in tinkering for solving given problems?* With this question, we aim to look for evidence of how the features of Tinkery 1.0 allow learners to solve engineering design problems with specific observable processes (Petrich et al., 2017) to determine that the problem-solving process followed by the learners aligns with tinkering. In this process, we also aim to understand how actions and interactions in the physical space aid the tinkerers in solving their problems, for which we observed the actions performed by the learners in solving the engineering design problems and their interactions within Tinkery 1.0 and conducted interviews.

5.1.2 The engineering design problems

Tinkery 1.0 is designed as a learning environment for problem-solving within engineering design domains. Based on the expertise and availability of the target population, it was further scoped to robotics, specifically using Lego Mindstorms, given its alignment with principles of tinkerability (Resnick & Robinson, 2017) and our familiarity with its components. The problems of Tinkery 1.0 had to be open-ended i.e. have room for personalisation and could be approached in several ways and to ensure that they had to have a *low floor* i.e. a basic solution to the problem can be built easily, a *high ceiling* i.e. the solutions could evolve to be very complex and refined; and *wide walls* i.e. there could be several solutions and many ways of the solving the problems. As discussed in our theoretical basis, there had to be a set of problems that had to complexify progressively. The parameters we used to determine the complexity of the problems were the resources required, the number of concepts that could help solve the problem and the number of variables that had to be controlled. Different permutations and combinations of these parameters could lead to a different problem set. The final parameter to consider was when the problems had to be solved.

We explored many sources like problems from known Lego-based robotics competitions, different challenges from Lego and the problems provided by their model set. Most challenges subscribe to an obstacle course that vehicular robots have to pass, usually set in a varied setting like a desert. Some advanced competitions had robots that could outrun each other or fight. Ones that spanned over months required some specific objective like a food assembler. Based on the broad themes we explored, we decided to keep the problems under the broad aspects of building a robot to achieve an objective like moving from point “A” to point “B” by moving. To keep it open-ended, we used the words “robot” / “bot”, and the way the learners can achieve motion was left to their imagination. To try and understand the possible solutions that could be built, we did try models based on gait motion (legs), tank belt-based motion, and 2 to 6-wheeled robots. We built A few examples from the Lego manual and some from our imagination. We tried simple to very complex robots, which gave us a better understanding of the time required to build and code them.

To make problems progress in terms of complexity, we then chose to break the problem into several parts, adding variables the learners had to control. We chose to have the learners first build a robot that could travel forward and backwards, then have it move left or right. Once that was achieved, we asked the learners to make the robot go from point A to point B in a room with furniture, and the robot had to avoid crashing into them. Initially, the learners were allowed to remotely control the bot with the brick buttons / Lego Commander Application / building their remote. The idea was to experience the actions the bot would have to perform to achieve the objective. Once that was completed, they were asked to program the bot to complete the task where they could not control it once the program was executed. The learners were allowed to program the path into the bot explicitly. Finally, the target was to get them to make the bot go from A to B autonomously without explicitly feeding the path. This could be done by using ultrasonic and colour detection sensors. To ensure the learners get opportunities to explore the affordances of sensors, we introduced two challenges which were also progressive among themselves as the first challenge could be completed by just using the ultrasonic sensor, which had only one affordance, and the second challenge could be completed with the multi-light sensor where one either had to use the reflective index or the colour sensing property of the sensor.

We had three challenges for session one, where the simple, functional objectives gave more room for exploration. The second season had one mandatory and one optional problem given only if the first one was completed, where both of them substantially increased in complexity and the number of options available to solve the problem, hence requiring focus play between resources and their idea. In the third session, we had one problem extending the previous one but forcing them to decide between several conceptual options like which sensor to use and many ways of achieving automation, with each sensor requiring several iterative cycles of exploration and play. Based on our trials to solve these problems, we realised two and a half to three hours was a good enough time for one session, which was ample enough for not feeling the urgency to solve quickly or long enough for completely getting lost or losing track.

To summarise, we had three sessions of three hours each, on consecutive days. On day one was session one, and the challenges were as ***Challenge 1:*** *Use the Lego brick with any sensor deemed fit to measure the area and the volume of the room you are in.* ***Challenge 2:*** *Use the Lego brick with any sensor to sense the following colours and identify them on the Lego brick screen. The colours were given as small blocks of red, green, yellow, blue, black and white.* ***Challenge 3:*** *Build a bot that can move forwards or backward.* Challenge 1 requires the learner to explore the ultrasonic sensor and the serial monitor of the Lego Mindstorm. The catch in the problem is that the learners must realise that the sensor has a limit of the distance it can accurately measure what they are not told and have to find it out and figure out a way of measuring the room, which could be done in several ways. Challenge 2 requires them to use the multi-light sensor to detect colours. This sensor can measure an IR reflection intensity that differs for every colour, or it has an inbuilt RGB-led reflection sensor which measures the intensity of the reflected coloured light, thereby determining the colour being detected. The learners have to use the serial monitor switch function, which they have been made aware of, to realise that there is a colour-sensing mode which is more accurate than the IR reflection mode. Finally, challenge 3 is very open-ended, where learners build a bot to move forward and backwards. Most of the details have been left to the learner's imagination, like the number of wheels, no wheels, motor powered / hand powered, etc.

On day two (session two), the problem given the first one was mandatory, and the second one was optional and only given if the first one was completed. The problem given for session 2 was "Build a bot that should be able to go from a point A marked on the floor to another point B marked on the floor, avoiding everything that is there on the floor using the control buttons on the brick or the app as a remote control or by building your own remote" and the extension problem was "Make you bot travel from A to B without controlling it manually but programming the path into it." The floors were laid with standard 12-inch grey coloured tiles 6 x 12 tiles on the floor. The boundaries of the tiles were visible, making a natural grid with intersections on the floor. There is a round table in the middle of the room and points A and B are at diagonally opposite ends of the table on the floor, requiring the bot to move and turn at certain angles to get from point A to point B. These tiles on the floor act as a perfect reference, especially when coding the bot on how much to move the bot and when to turn, but again this is not explicitly mentioned and is left to the participants' exploration. Here the challenge was for the participant to decide on the kind of bot they would build, as continuing with the bot from the previous day was fine but not mandatory. They had to figure out if they wanted wheels at all, and if they did, then the number of wheels they wanted to use, the number of motors and on which wheels and finally, how to operationalise the turn by either building a steering mechanism or moving opposite motors in opposite directions. For the extension problem, they had to figure out how to move the bot for a given particular distance either by using no. of rotations on each wheel or degrees of rotation of each wheel and for how long the wheels should rotate. Similarly for making a turn when and in which directions should each wheel turn for it to reach point B? Adding to it the tiles surface and choice of wheel size would vary the amount of slip and the shape of the bot would vary how and how much the bot turned. Hence the learners had ample opportunities to play with the resources they had and their ideas and if required explore more to find new pieces and new ways.

Finally, on day three the participants were given the extension problem from day two and then asked "Make your bot go from A to B without explicitly programming the path. You could program it to react to events or objects that you may place in between", the idea here was to make them think of how the bot could be used to perform the same task even if the location of the points was changed. They now had to choose between using distance to trigger an event or using colour to trigger an event, like go straight, turn right, etc., and then use these triggers by placing objects around the room to make the bot act the way they intend to. Additionally, when programming for this problem, they had to figure out how to code the decision i.e. use switch statements and figure out a way to ensure the detection code keeps running or use always running parallel blocks, each trying to detect a different colour and move accordingly. Even though theoretical, it might seem straightforward,and we see in our findings how implementing it physically leads to challenges one fails to foresee. There were a lot of other aspects, like time spent mentoring etc, to be considered, which have been discussed in the following subsection.

5.1.3 Research Design and Participants

The broad study design was aimed at understanding the actions and interactions of the learners with Tinkery 1.0, the pedagogy and the mentor guidelines. A preliminary session was conducted with a research assistant as the participant and me as the mentor working on an alternate research problem in the same domain. Other sessions were conducted with me as the mentor to understand the learners' interactions with Tinkery 1.0 and its components through their problem-solving journeys. A summary of the broad study design is shown in Fig. 5.1.

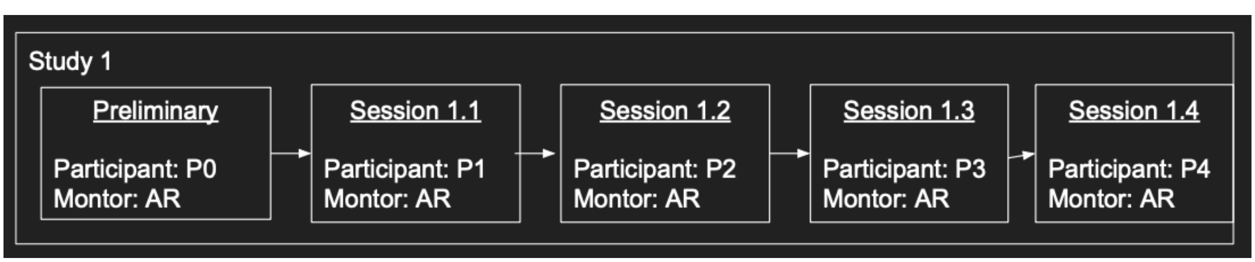


Figure 5.1: Broad study design for DBR cycle 1.

Operational challenges from the preliminary study were worked out. A few modifications, like the camera's placement for data collection and arrangement of the building resources, were modified based on the preliminary. The workshop was spread across three days; where on day one, the participants were given an introduction to Lego Mindstorms followed by a post-session reflection interview making the learner reiterate what they did in the entire session. The learners were only asked clarification questions not to bias their problem-solving approach. Session two the next day started with a recap of what the learner did in the last session and then gave the second-day problem. The recap answers the question *"So what did we do yesterday ?"* given by the learners themselves. After the session was over, a similar reflection session as on day one was done where the participant would just talk about the session, and the mentor would ask clarifying questions to make the participant speak more. On the final day, the day again started with a recap, but only two and a half hours were given for the problem to be solved, followed by 30 minutes of reflection and an interview session. During this session, the mentor delved deeper into knowing the problem-solving process of the learners based on the observational notes and using stimulated recall by showing them what they were doing on video, which was being recorded. Additionally, the mentor gave them a problem for which they just had to talk about their intended solution/solution approach with Lego Mindstorm and were allowed to point out or show things they would use or how they would use them. A summary of the study is shown in Fig. 5.2

The most appropriate participants for our research studies were the learners from undergraduate courses in engineering. There were no limitations in terms of experience in doing projects, workshops, hackathons, etc., as long as they had not used Lego Mindstorms extensively. For participant selection, a call was circulated among the undergraduate students of our institute for a Lego Mindstorm Robotics workshop. Based on their prior experience with Lego Mindstorms, which we preferred to be minimum, we shortlisted five candidates on a first come, first serve basis keeping three more in case any of the shortlisted ones did not show up. The participants from this age group have just begun their training in engineering and have joined after two years of strict analytical training with a minimal experimental approach towards problem-solving which is required for the entrance exam. We could only complete studies with two participants as that is when the institute closed for lockdown, and the study participants had left the campus. Eventually, we also had to leave.

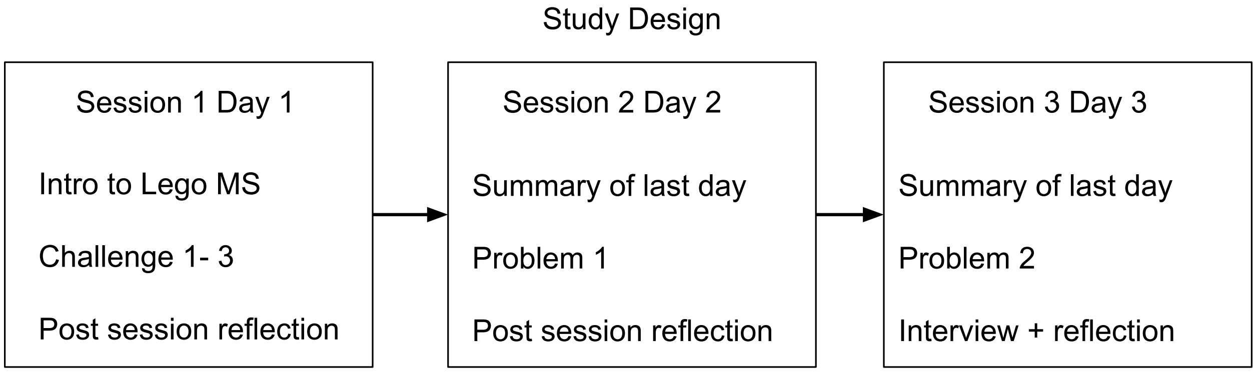


Figure 5.2: Study design for every participant.

We tried many options in terms of redesigning the solution for a topic where online resources could be used. We tried to figure out the logistics of transporting the robotics kit. We designed and experimented with online platforms for conducting studies remotely. Finally, we conducted a small study with a participant from the 9th standard who was geographically located so that the robotics kit and some personal assistance could be made available to them. The mentor logged in remotely. For this participant, four sessions of the study were conducted across four days, wherein the first session was an assessment of how the study could be conducted, and the rest of the three days were as shown in the study design. A total of four participants took part in the study. On the first day, during an introductory session with the participants on the first day, they were asked about their exposure to robotics from their formal and informal education. Later in the discussion, we also talk about the role of their prior knowledge in their actions and interactions with Tinkery and, at times, their problem-solving process.

5.1.4 Procedure

As discussed in the previous section, every participant participated in three sessions of three hours each, preferably on consecutive days. The Focus of each session, as discussed earlier, would vary from exploration to getting to know what is available and getting a sense of ideas that one gets; play for building one's idea as a physical artefact; and finally, thinking of evolving one's physical solution. This aligns with our pedagogy *Xpresev* and our operational understanding of tinkering as iterations of exploration and plays to evolve solutions. The primary objectives of each phase are described in Table 5.1. The primary objective of each session determines the focus and design objectives of the activities and learners' goals and does not try to influence the problem-solving process of the learner. The learners are free to explore, solve (experimental play) or think of evolving the solution at any time and need not do it in any sequence.

Table 5.1 Operationalisation of pedagogy in Tinkery 1.0.

Session	Primary Objective	Activity Focus	Learner Goals
1	Explore	Explore resource affordance and use them to solve candidate problems	Understand and use resources based on their affordances Determine the affordances required for their solution approach.
2	Solve	Solve problems by finding solutions for subproblems with the given resources.	Divide a problem into subproblems & identify required affordances. Use resources based on required affordances OR solve sub-problems based on the affordances of the resources available.
3	Evolve	Improve the solution to address new or emergent challenges.	Reflect on previous knowledge and experiences. Improve the solution by iterating with alternate possibilities, resources and affordances.

The studies have been conducted in the study room in the research lab of IDP in Ed Tech, IIT Bombay. The study room is accompanied by an observation room with a huge one-way glass window, as seen in Fig. 5.3. The entire Lego Mindstorms setup is arranged on a table with a computer, some partial-manipulable and some space to work. The computer has a programming environment and internet access.

In session one when the learners arrive for the workshop, they are taken to the study room, and the study happens as per the design. The session's focus is to ensure that the learner's experiments with Ultrasonic sensors and IR / Color sensors can understand the affordances of Distance measurement, colour detection, and proximity detection. Beams, pegs (3 types), Wheels, frames and angle joints to understand their affordances in different forms of construction and connection. The Lego brick, its ports and slots, its top buttons and the live view to understand the affordances of data display, brick and buttons as controllers and ways to connect sensors/actuators or the brick in construction. To ensure the learner does the exploration, the mentor must observe the learner's direction towards the solution approach and provide the following prompts. Provide direct operational information about component use or method of use. Use Questions to trigger reflection. E.g. ``Why did you drop the previous idea ?” Encourage play to look for feasibility, e.g. ``Why don't you try it out” and direct them towards the scaffold, E.g. “See how it has been used there ``.The mentor assumes the role of a co-participant in this session. The session ends with a reflection on things done throughout the session.

a) b)

Figure 5.3 a) Study room with a one way mirror, b) Observation Room

In session two on day two, the focus is for the learner to play with the components to solve the given problem. A few objectives for this session: building a 3 / 4 wheeled bot that can turn. By choosing between a 2-motor or 4-motor design, determining the algorithm driving the motors to enable turning right, left or back, finding a structure that allows swift turning of the bot, and building the bot in a way it could be physically driven by the brick buttons, using the push buttons to build a remote and for the autonomous mode based on programming, estimating the distance to be travelled and finding equivalent rotations to be programmed and estimating the rotation direction and angle for each motor to make a left and right turn. To ensure play from the participant, the mentor must observe the learner’s actions on the components being used and encourage them to experiment and play. The mentors could rely on triggers for the same. The triggers could be in the form of reflections on days 1’s ideas and approach. There could also be rain checks to know if the learners are stuck in idea/coding/construction/exploration and provide alternatives via analogies like 3-wheel vs 4-wheel design. Algorithm for turning, estimation of motor rotation for a distance/turn. Getting the brick on the bot, body scale for rotation. Keep doing status checks. Encourage them to take a new approach when stuck for wheel configuration, structure, and coding constructs. If the learners seem stuck, the mentor should ask questions leading the learner to alternate solutions and ensure they reflect on actions once they are unstuck. The mentor's role in session 2 is more of an instructor.

In session three, on day three, the learner focuses on experimenting and playing with the sensor components to advance their robots using scissors and program even-based actions. The mentor here focuses on getting the learners to do a lot of exploration and play cycles to get them to work on their ideas by building them. By session three, the participants are expected to have become well-versed with the component affordances and use them to build their ideas physically.

5.1.5 Data Sources

Video data is used to understand the Interactions with the resources and the resources they use to build the solution. Observation Logs are used to mark episodes of interest or log questions for the interviews. The interview logs are used to analyse the participants' perceptions or triangulate observations made by the researchers.

Videos are recorded from the table top view, which focuses on the activities happening on the table and a side view which captures the learners along with the table and the room view to capture the actions performed by the learners in the entire space. The side view camera is kept in the observation room to reduce the number of cameras in the visual field of the learners. Additionally, the computer system records the screen to capture activities happening on the screen, and the inbuilt Facetime camera also records the audio and interactions between the learner and the mentor. The Facetime camera is non-intrusive and also acts as a backup camera that provides audio and some video in case other cameras fail to record.

The post-session interview was also recorded in video and audio as the learners sometimes pointed at things and performed some actions as part of answering the questions. The initial questions of the semistructured interview were open-ended to get the participants to talk about their prior experiences of making and building. Using the answers from the opened questions, the interviewer used probing to understand the exact exposure of the participant and their interests. After each session, the participants were asked to articulate what they did in the entire session to enable reflection. Also, to clarify certain actions that the participant did, the participant used stimulated recall by showing them the actions they had performed. After the final session, the semistructured interview was conducted to understand the affective changes and internalisation of the resources. This was done by asking them to solve a problem and discuss the solution. The interview questions were also based on notes made by the mentor to triangulate observations made. Additionally, some questions were about their affective states before and after going through Tinkery 1.0. The interview ended with a hypothetical problem that the learners had to explain how they would solve based on the resources available. This was to gather evidence of learners showing indicators or mediating processes that suggest tinkering and reflections on how learners use ideas and resources. A sample of the guiding script for the semi-structured interviews has been provided in the appendix.

5.2 Data Analysis

The analysis method was interaction analysis (IA) (Jordan & Henderson, 1995). It employs transcription conventions. However, IA focuses on phenomena, including learning, that go beyond the structural features of talk-in-interaction. IA treats material artefacts and embodied conduct as obligatory aspects of the analysis. IA is designed to produce descriptive analytic accounts. Such accounts are inextricably tied to particular occasions as meaning-and-use and intersubjectivity are situated matters that cannot be studied isolated from the settings within which they were produced. Our goal is to understand learners' interactions with the elements of Tinkery as they tend to tinker to solve engineering design problems. Hence we chose to go with IA. There are various interactions among the learners, the resources they build with, the environment they act in and the conversation they have with a mentor. These are physical, and observable and provide insights into the learners' material use and embodied conduct.

For the 4 participants over three days, we had 12 sessions of three hours each to be analysed. The analysis was done as follows:-

1. First pass of videos to identify episodes of interactions between the participants and the resources of Tinkery 1.0 like Lego, partial-manipulable and the mentor leaving episodes where they were idling. This pass resulted in 10 to 13 episodes per season ranging between three to ten minutes which gave us around 30 to 40 episodes per participant.
2. In the second pass, we write a narrative for a few after sorting, merging and finalising the episodes based on relevance to RQs or something interesting that emerges. After the second pass that resulted in the rejection of a few episodes and the merging of others, we were left with 8 to 10 episodes per participant.
3. Interpreted the episodes from the lens of tinkering-based interactions and code using learning dimensions of the tinkering-based activities framework. We generated 3 to 5 major narratives per participant through the interpretations, merging the episodes.

4. These narratives were then used to gather evidence for detailed design conjectures.
5. These narratives also provided some emergent findings when analysed with the process lens.

The data from participants of DBR 1 finally resulted in 16 narratives. We have presented evidence from 7 such narratives in support of the conjectures. Additionally, the evidence is also suggestive of a few new findings. Not all conjectures have supporting evidence, in which case, the narrative also helped us identify challenges that have been addressed in the next revision of the learning environment in the next DBR cycle.

To analyse data for interactions, we choose evidence from various participants, which mainly consists of episodes of the actions of the participants to build their ideas into the physical space or tackle the challenges faced. To present the evidence, the choice of episodes is based on maximum variation (heterogeneity) sampling (Patton, 2014). Different participants have been found to choose various methods to solve a problem through persistence broadly. We also observed in some instances that the same problem-solving processes led the participants to work in two different ways. Hence based on the theoretical replication logic (Yin, 2017) of the same outcome from two varied ways, we provide evidence for the variations in several conjectures.

5.3 Findings

Snippets from the narratives discussed above were used to identify supporting evidence for the conjectures. These snippets are termed *episodes*. We discuss details of six conjectures from scaffolds, problems and mentors' roles to give evidence. The rest of the conjectures have been discussed in Appendix II. Additionally, for each conjecture, many similar episodes across participants' narratives account as evidence, but we present a few representative episodes as evidence. A summary of findings for all the design conjectures has been discussed at the end of this section.

5.3.1 Findings for Design Conjectures on Scaffolds

- **DC1:** Partial-manipulable encourages learners to engage in playful exploration and perform actions on built artefacts to seek feedback.

In the following episode, participant 1 would build a bot that could move forward and backwards. To do so, the participant was trying to attach the wheels and the motors. She was trying to figure out what to use to connect them, and that is when she spotted the partial manipulable.

Episode 1.1: *She took and looked at the partial manipulable. She looked at the frames and how they were connected. She says "Hmm, I could use this to build the chassis of the bot". Then she started connecting the frames in a similar way as they were connected in the partial manipulable. Through a few tries she was seen connecting the other components along with frames and building the chassis of her bot.. . . . . Later during the interview she mentioned: "The model kept there was helpful in getting to know how to build the structure of the bot as that's was I got the idea of using the frames and later saw the possibility that one could attach things to it".*

She discovered a partial manipulable used to attach two wheels using frames. That is how she discovered the affordance of the frames as a structural mechanism by referring to the partial manipulable. Through this reference, she was also able to determine ways of connecting other components to it, which helped her use them to build the chassis the way she wanted it to be. Here we observe that the learner was encouraged to use the frames as she spotted them on the partial manipulable, which she confirmed later during the interview. Here we see the learner can determine the usage of frames by referring to the partial-manipulable and using the as per their requirement. Participants often saw Similar instances, especially when trying to decide on the use of various pegs, beams and wheels during their problem-solving.

We also realised that since the partial-manipulables were limited to just beams, farmers, pegs and wheels connected in basic configurations, these were not referred to much as the problems progressed. Hence we believe we did not have episodes that support **DC2** and **DC3**. We have discussed this in detail with evidence as challenges of designing and using such partial-manipulable later in the chapter. We have tried to address this in the next revision.


Referring use of frame from partial manipulable

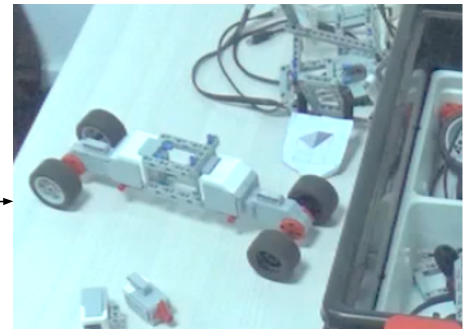

Using the frames to build the initial design

Figure 5.4: Design based on influence of the partial manipulable.

- **DC4:** Access to resources displayed according to Lego reference cards supports learners in performing actions on built artefacts to seek feedback, using materials in their own ways and developing workarounds.

In the following episode, participant 2 built her bot to move forward, backwards and turns. She had connected the wheels and body and wanted to mount the brick on the bot's body. The episode is set in this context.

Episode 4.1: *To stabilise the bricks on the frame she needed to connect the brick to the frames and to do so she looked at the pieces arranged and reached out and picked four types of pegs. These pegs were all arranged as per the Lego kit and the pegs were kept in separate sections of a tray. Then she said, "These double-frame black pegs don't work". As she examined them she kept the short double-frame black connectors to her left hand then picked the red connectors which she compared visually in terms of the length by keeping them together and the head cross-section visually. She then rejected the pegs as it seems she wanted something else she took the brown peg and the blue pegs. She looked at them for a while and then chose to go with the blue pegs which are triple-joint pegs. She used one of the joints to connect the brick and the other two to mount it on the frame.. . . . After she has attached the brick she removes the motors and adds blue pegs along with the black ones to join the motors. Then she presses the brick on and we see the motors and the frames are holding fine.*

We see the learner is trying to connect the brick to the frames for which she knew she needed pegs but was unsure which one, so she picked the black ones as she had been using them previously. However, several other pegs are available, classified into sections to ease the search for components for making a connection. She attached the black pegs to the frame and examined the brick, as seen in Fig. 5.5. That is where she realises that the black ones can just connect two things, the brick and one frame on the body or the two frames on the body using up all the slots. Then she looks at the other blue sets of pegs available next to the black ones and compares them visually, and through a trial, she can identify the blue ones that worked for her. Since the blue ones are triple joint pegs, they can connect the brick and the two frames, whereas the black pegs were either connecting just the frames or the brick with one frame while using up all the slots on the frames. So the presence of the pegs in the visual space and their classification assisted her search in narrowing down the space the pegs were through the action of inserting the blue peg made her realise that with the new pegs, she was able to join the relevant piece for the idea she wanted to pursue which was achieving a double joint between the brick and the two frames in the base. Hence, the visual presence of the peg led her to perform an action that led her to realise that such a peg could address the challenge of connecting multiple pieces.

Interestingly further, we see this new realisation allows her to make the older joints between the motors and the frames stronger as she adds the blue pegs in the motor frame joints also, as seen in Fig. 5.6. So the idea of creating stronger joints has been released with the help of discovery of new resources and actions made with them. Then it helps the learners realise them by using the resources they want, which in this case is using the blue double joint pegs to strengthen the joints.

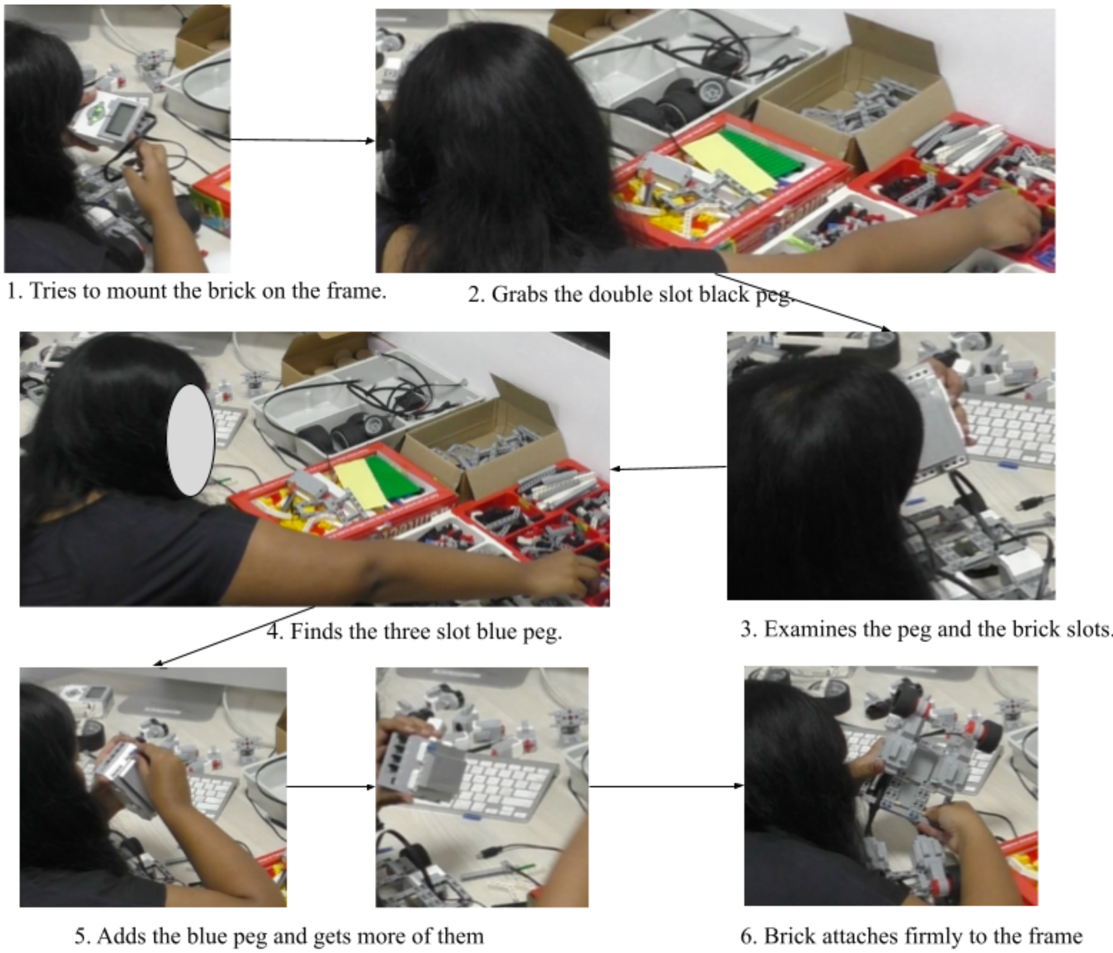


Figure 5.5: Learner discovering pegs based on the resource arrangement

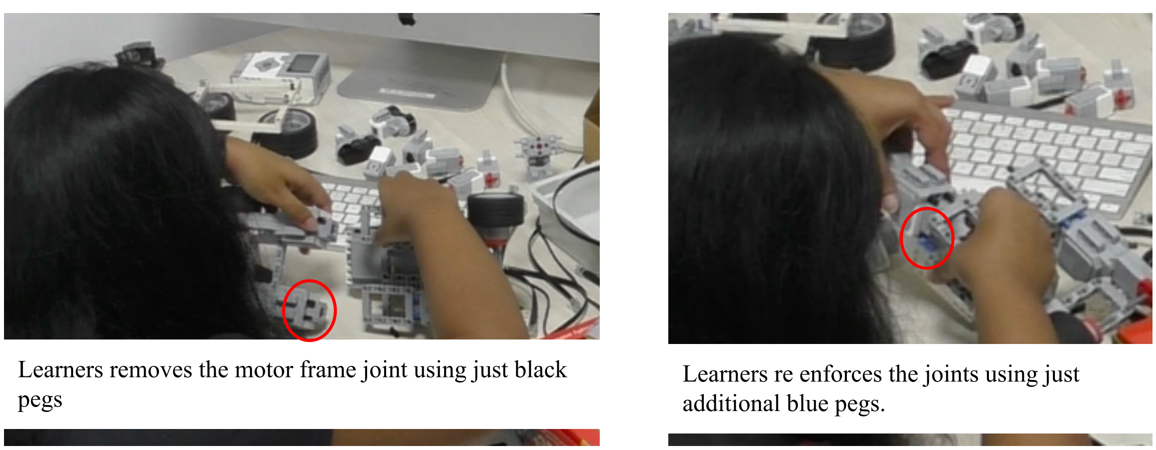


Figure 5.6: Learners is seen modify their approach towards joints based on new resource discovered.

In other words, it helped her persist towards realising her ideas. Similar instances are seen with all the other three participants several times during their problem-solving.

This way of arranging resources did allow learners to find the pieces they desired, but the search often required assistance from the mentor. Additionally, there were many pieces on the cards whose functions the learners could not determine and required the intervention of the mentor. Additionally, evidence for arrangement supporting playful exploration still needs to be seen. We will discuss these in detail later in the challenges where we realised that functional classification may seem more intuitive than visual referencing, something that was realised by looking at such narratives.

5.3.2 Findings for Design Conjectures on Problems

- **DC6:** Problems in the physical space allow learners to perform actions on built artefacts to seek feedback and troubleshoot iteratively.

In the following episode, participant 2 is seen coding her bot to move straight for the first time. She is sequentially using independent blocks to control all four motors.

Episode 6.1: *To move the bot forwards the participant chooses the run block and sequentially adds four blocks for each motor to run forward for one rotation. As soon as she executes the program she looks at the bot at and sees that the four wheels move one at a time. Initially she seems confused so she executes the blocks again and then she realises that coding the block sequentially moves the motor one at a time and not all the motors would move forward together.. . . .*

Now that she has figured out how to execute the codes in parallel, she has selected the direction forward for both the blocks yet two wheels tend to turn in reverse and two wheels tend to turn forward. She asked the mentor "Are both the commands actually getting executed at the same time? I do not think they are". The mentor replies " if you select both the blocks or just click on "run all the blocks", all the blocks that have the "start when play block" get executed." The participant shows her code and says she has coded for all motors to go in the forward direction. The mentor then looks at the robot and nudges her "observe the front and rear wheels independently". She then exclaims "oh!

two of the wheels are mounted as reverse whereas two are mounted forward". Then she says "to move all of them in the forward direction I will have to set the movement direction in reverse for two of the motors and forward for two of the motors." . . . . .

Later on the same day in the same session she had to figure out how to turn the robot. So she coded one of the forward motors to turn forward and the other forward motor to turn in reverse expecting the robot to turn. But when she executes the commands she sees that the robot's wheels are spinning but the robot is not turning. . . . . . (After a number of trials and reflection from the mentor presented in episode 11.1 she realised that the rear wheels are not letting the bot turn.). . . . . . She had tried to turn all four motors but was not able to find a suitable combination code block to achieve that. . . . . . (Eventually after a few mentor interventions which have been presented as episode 10.1). . . . . . She looks at the bot and turns it with her hands and says "If I turn the diagonally opposite wheels that should be enough to turn the bot." . . . . . . (Refer episode 9.1 for details of how she got to using the set motor rotation blocks to control the two diagonally opposite motors and determine that coding left can make the bot go straight and coding for straight makes the bot turn). When she executes the code blocks she observes the bot turning but taking a lot of time and effort to turn and that it would be very very slow. . . . . . . (after a few mentor nudges to observe the challenge and then workaround mentioned in episode 9.1) . . . . . . she removes the rubber tyre from the two diagonally opposite wheels reducing the frictions and now when she executes the command to run the other diagonally wheels in opposite directions the bot is able to execute a turn.

As the problem requires the participant to move the bot physically in a space she is programming the logic and making the bot perform actions in the physical space in quick cycles of ideation and experimentation. These actions uncover challenges like motors mounted in the opposite direction but programmed for the same direction or misconceptions like the sequential placement of blocks vs parallel execution of blocks. Based on feedback the bot provides by behaving as per the code uncovers these challenges and misconceptions, like the bot would require parallel execution if individual blocks for movement were to be used. Similarly, she can observe that even though the blocks have been coded for the forward movement, two motors are mounted in reverse; hence to make the bot move forward, two will have to be moved in reverse. This was easy to discover as the action could be performed and the result seen instantly physically happening. The evolution of her code and the design are shown in Fig. 5.7.

In the second case; the bot should turn logically. However, it is not turning as there are certain aspects of the bot's design, like the centre of rotation when using just the two forward motors to turn or the diagonally non-powered wheels attached to the motors not moving freely that she has not accounted for. The advantage here is that she can see these happen physically, and by doing some actions on the physical objects, like trying to rotate the bot, she can realise the challenges and quickly test out ideas that she thinks could be the probable reason.

In a similar episode, P1 figured out by the observation that she had not considered that the wheel could spin when running the bot on the tile floor. She had coded the number of degrees the wheels should rotate to determine the distance the bot should move before taking a turn, and the slip made the bot turn earlier. She discovered this and later recalculated the number of degrees with an approximate offset to the degree of rotations. While moving her bot, P3 could observe the fragile nature of the font of the bot, which she correctly claimed would have to be fixed for the bot to move appropriately. Then by observing the reason for the flimsiness, she was able to address it via various observations and trials with different beams. Even P4, on many occasions, was able to uncover challenges and work around them by observing the behaviour of the physical artefacts and accordingly troubleshooting. A lot of similar instances were observed for all the participants.

Hence being situated in the physical setting allows the learners to build their ideas as physical objects and perform actions on these physical ideas to gather feedback and iterate accordingly. Through these actions with tangible objects, while situated in a physical setting, the learner can identify the challenges and variables to control and control them to reach her determined objective. This helps them perform quick and focused cycles of exploration and play. This, as we see here, can be achieved by situating the problems in a physical space and making the learners work with physical objects in the physical space.

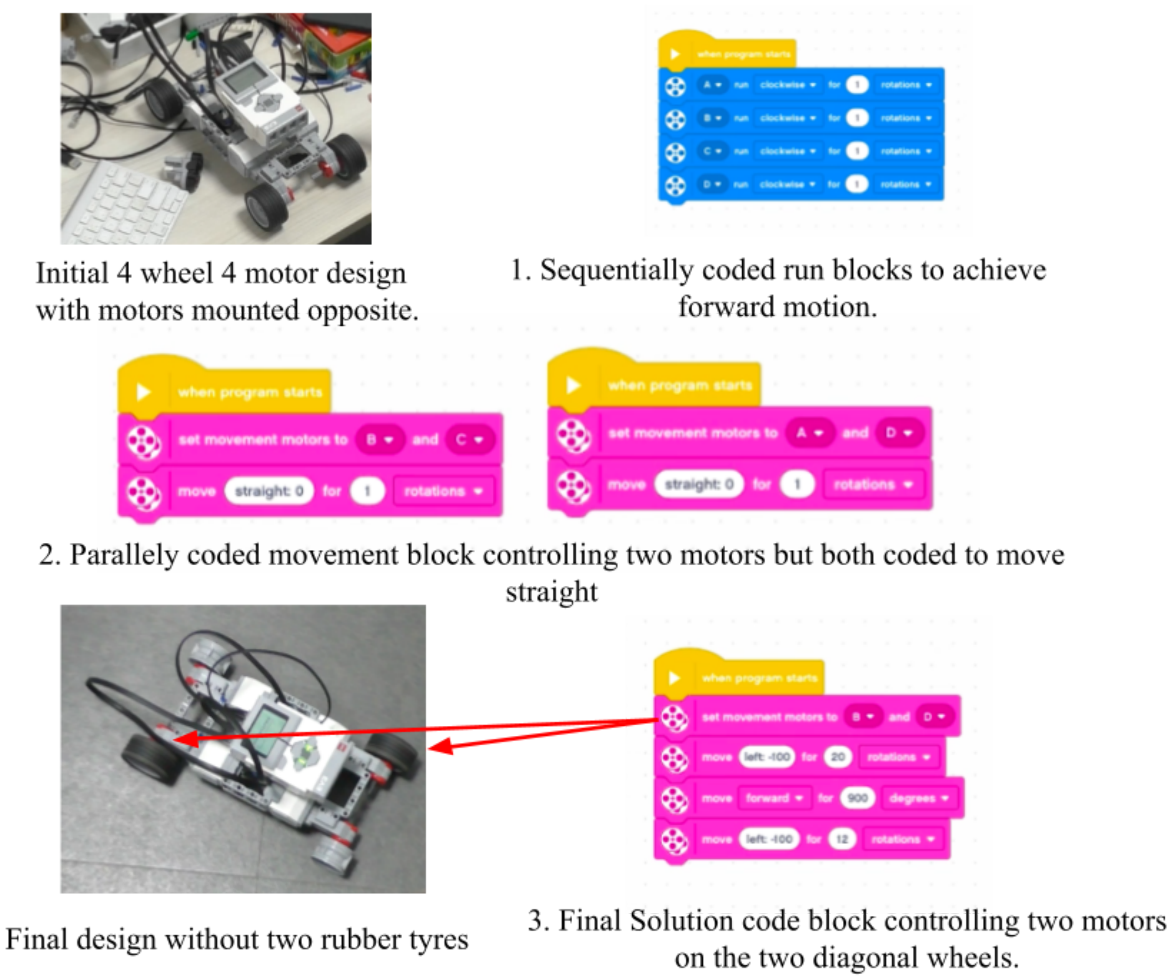


Figure 5.7: Evolution of P2's code for making the bot go from point A to point B

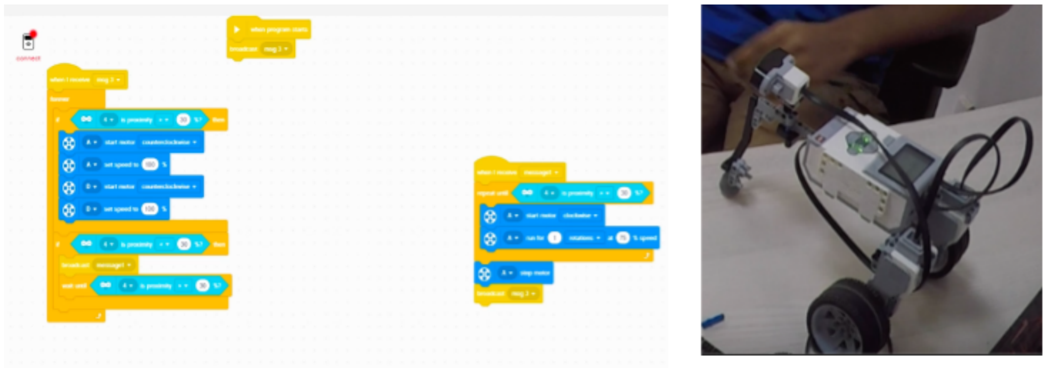
5.3.3 Findings for Design Conjectures on Roles of Mentor.

- **DC10:** Reflections triggered with questions direct learners to engage in playful exploration and perform actions on built artefacts to seek feedback.

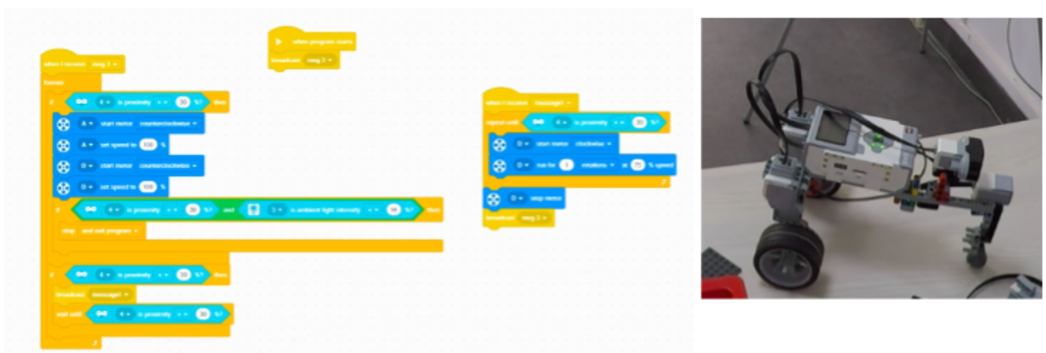
  Episode 10.2: *The participant has been thinking of a new logic as he looks at his obstacle avoidance code. (P4 has a habit of thinking out loud hence he talks to himself at a number of instances). He starts to talk out loud and says "If I code the threshold more than the current (obstacle avoidance) one then the bot will stop and never turn but if I code it less than the current threshold the code will never reach it so it seems I am doomed". The* *mentor hears it and intervenes "How do you think you can solve this challenge?", the participant responds and says "somehow I need to differentiate the condition for stopping and for turning" and then he pauses looking at different blocks available for the proximity sensor. The mentor then says "Had you considered any different methods initially when you chose to go with the proximity sensor?". Participant looks at the mentor with a stare and then says "Oh! Oh! Wait ! don't say anything more, I could use an ultrasonic also to measure distance any use that to stop." and he moves to the screen and looks at the blocks for the ultrasonic sensor and after a while says "But even with that I will have the same mess! The lower threshold of the ultrasonic is very high that is why I did not use it in the first place". Then the mentor asks "How did you find that out?". The participant then says while looking at the tray of sensors and picking the Ultrasonic sensor "In the first problem when I was measuring the size of the room", then he takes a pause and looks back at the tray and says "Oh! I could use this" (picking the reflection multisensor he used on challenge 2 on day one to identify colours) with a smile he gets on to attaching the sensor. Mentor curiously asks "How do you plan to use this" to which he replies "Wait I will show you". . . . (he spends some time attaching the sensor further ahead of the proximity sensor) . . . Once the sensor has been attached he picks the bot and places it at point B near the door and using the portview (serial monitor) checks the value of reflection. He uses this value and programs it into the code using a composite conditional statement to stop the bot. Then he keeps the bot at point A and then executes the command. The bot starts, reaches the first wall and takes a turn towards the door where point B is and reaches point B but does not stop and continues to move and hits the door. The participant continues to see that and says "Now what happened?". The mentor questions the participant and says "what do you think is happening there?". Listening to this he picks the bot and stops the execution. Then he opens the serial monitor for the reflection multisensor and now keeps the bot short of point B and looks at the value from the sensor and gradually moves the bot towards the door. Then he does the same action from an angle. Then he goes back and changes the threshold value for the reflection multisensor and loads the program. Once the program is loaded he places the bot back at point A and executes the command. The bot again goes towards the wall and then turns left towards* *the door. As the bot reaches point B it stops. The participant exclaims, "yay! Let us try once more.". The bot reaches and stops at point B in all the subsequent runs.*

When the participant was stuck, the mentor asked him about his approach when he had first thought of a solution for this challenge. The mentor's objective was to trigger him to reflect on the broader problem of measuring the distance between the bot and the obstacle and not limiting the focus to finding a conditional statement for the proximity sensor that could be used to differentiate between stopping the bot and turning the bot. The participant started by just answering the question, which led him to explore the sensor tray and eventually found the sensor he thought he could use. Again when he executed the code for the first time after attaching the sensor, he seemed confused about why it did not work. When the participant questions him about the reason for the bot's behaviour, he picks the bot and starts looking at what values are observed when the bot closes the door at point B and then tries various angles. The changes in the approach are seen in the design and the code of P4, as shown in Fig. 5.8. Here we see that reflections triggered by the mentor with questions and not directly giving out the information allow learners to explore more and take actions in the physical space and use the feedback from those actions to achieve their goals further. Another exciting thing we see here is that using questions to trigger lets the learner remain in charge of the decision, which is essential to them, as we saw when the participant asks the mentor not to tell them anything more.

Similar instances were observed with all the participants on several occasions, especially when they were stuck, or things were not going as planned. All the participants later in the interviews also claimed "they" were able to solve the problems. Two of them also specifically mentioned this way of asking questions to assist the learners towards a direction and let them continue solving the problem. So question-based reflections the participants can engage in exploration and take actions that allow them to continue solving. At the same time, the agency of the solution and the solving process remains with the participants.



1. Code with just the proximity sensor using a threshold to determine when to turn.



2. Code with the proximity sensor and the reflection sensor to stop the bot.

Figure 5.8: Evolution of P4's bot with addition of a sensor to make it stop at the point b.

- **DC12:** Prompts and checks from the mentor nudge learners to engage in playful exploration and perform actions on built artefacts to seek feedback.

In the following episode, participant 3 built a three-wheel bot and made the front wheel steady (as seen in episode 4.2 in Appendix I), and she was to test it for the first time. Upon execution, she realises that there is some issue with the bot. So she and the mentor are conversing, as we now see in episode 12.1.

Episode 12.1: *The participant now wants to make the bot turn by making both the wheels on the left to move clockwise and right ones anti. When she tries the remote the bot doesn't move. She picks it up and keeps it up and tries random combinations of ports and the motors they connect to. The mentor asks "Try observing how the individual wheels are turning when you move the joystick." She then keeps the bot upside down and tries to move the joystick to the left on her app remote. She sees the left wheels turn in opposite* *directions. Now she connects the right rear wheel to the brick port on which the left rear wheel is connected and similarly connects the right wheels. So now when she moves the joystick to the right all the wheels move forward and when she moves the joystick forward the left and right wheels turn opposite and the bot turns left. Then she says "Is it ok if I manage to move the bot this way?" to which the mentor replies "sure". So she controls the bot to move straight and back by moving the joystick right and left; and then turn it by moving the joystick up and down. . . . . After completing the task of manually taking the bot from point A to B she says "I guess the remote requires the specific wheel motors to be connected to specific ports and I might have had them connected opposite hence the bot was behaving opposite to the directions the joysticks were being moved.*

Here we see that the prompts from the mentor make the participant observe the behaviour of the wheels based on the actions done on the joysticks, also shown in Fig. 5.9. This helps her figure out the reasons and a way of getting the joystick to work. Here the prompt makes the participant gather attention and stay with one aspect of the solution allowing her to figure out the challenge. Eventually, we see that the participant is also able to determine why the joystick and the bot were behaving in an opposite manner where we could say that making her observe allowed her to play with the joystick and the wheel directions and through the changes she had figured out that specific motors (wheels) would be required to connect to the specific ports to control the bot as per the direction specified on the joystick.

Figure 5.9: P2 tests the remote app then past the nudge from the mentor observes the wheels and then re configures the ports and the motors by changing the connection of the patch cords.

Based on the episodes above from P3 and P2 and several similar episodes from P1 and P2, checks and prompts from the mentors nudge the learners into playfully exploring or taking actions in the physical space. Additionally, These nudges help them observe the behaviour of their artefacts concerning actions making them reflect on the feedback they receive from doing those actions which in episode 12.2 were observing the wheel when moving the joysticks and in episode 12.1 were moving the wheel of her bot with her hands.

- **DC15:** When mentors avoid prompting they allow learners to use materials in their own ways and express ideas and emotions as artefacts and actions.

In several episodes, the mentor always uses questions to trigger reflection and never gives out any direct information. This is essential for the participant to remain in control of the solution process and the final solution. In certain instances, the mentor will foresee challenges as in the case of P1 and P2. They started with a 4 wheel bot design and both of them were trying to turn the bot by moving just the front two wheels in opposite directions. P1 was doing this out of a misconception from her prior experience and P2 was doing it out of her inability to control all four motors. Even though the mentor was aware of the challenges they were about to foresee he let them continue the path and both of them were stuck in the same situation as we see in Fig. 5.10. Even here the mentor made them observe and reflect on what was happening and allowed them to choose the way they would want to proceed. Both of them choose to go their paths where P1 uses only two wheels and a caster wheel, whereas P2 still chooses to go with four wheels by controlling the diagonally opposite wheels. In the case of P3, the mentor knew that she had connected the wheel to the cross port that would not let it move freely yet he chose not to point it out. Later when P3 was stuck, he made her observe and reflect allowing her to discover where the problem was and then address it. Similarly, P4 determined that he could get the bot to go from point A to point by directly building a bot that moves autonomously, the mentor allowed him to do so and after a lot of explorations and trials, P4 was able to get the bot to go from A to B autonomously. The following episodes were made when the participants were later asked during the interviews about their problem-solving process.

episode 15.1: *P1: "I feel this approach of solving problems is interesting. Here I am getting to experiment and I do not feel the pressure of not being able to do something and I have come to realise that eventually I found a way of getting out of the sticky situations. When you (the mentor who is also the interviewer) ask a question you make me think rather than giving me the answers and I guess that keeps me interested in solving the problem. I definitely feel confident about using the kit to solve more problems and I think I will be able to do it."*

P2: "I would be curious about each part. Like the black pegs do not create a very strong joint at times and you have to use the blue one. Now I see that I can reason out things that I have used in this project otherwise I would have just read the instruction manual and done it and now I am more confident that I would be able to tweak that robot than just build it according to instructions. Rather now I feel I would question myself like you (the mentor) has been questioning than giving the answers, which I think you already knew. I feel now if I have to figure out some new thing I will be able to do it more confidently as I realised that eventually we were able to get somewhere while solving these problems."

P3: "I had done a workshop on solar panels where they showed us how to assemble a solar light and the exciting thing about that was I got to keep the solar panels and lights. Here what I feel is I got to know of a way of solving problems by asking questions and I got to know about so many parts of Lego. I feel confident that I can make anything that I like. As I was able to solve these problems, Lego feels more fun. Earlier Legos just felt exciting to work with but now I am able to think of things that I can build."

P4: ". . . . . .I have worked with a similar mechanix kit but I had not thought Lego could get this complex and interesting, I guess it's more because you were not giving out answers and just asking those questions. But they helped. In thinking. The fun part was I was able to get the bot done by the end of it. Can we do more such bots? I have so many ideas that I want to work out.. . . . . "

P1's Initial four wheel design that would not turn then the final caster wheel design

P2's Initial four wheel design that would not turn then the final four wheel design

Figure 5.10: Similarity in P1's and P2's initial approach and variations in their final designs showing dealt with the same challenge.

What is common between all the statements is this approach of asking questions and the fact that they built confidence by solving the problems themselves and feel they can approach similar problems. Hence, the participants had a sense of agency throughout the problem-solving process. How they have developed confidence shows the importance of abstaining from prompting the participants and using questions when and where it is required. This helps them experience failure and find ways to overcome it with some reflection as and when required. Also, as they mentioned, they will eventually figure out how to get things to work out.

Apart from the episodes of conjectures discussed above (DC 1, 4, 6, 10, 12 and 15), we have discussed some additional episodes in Appendix I. We also found evidence for the following conjectures, which have also been discussed in Appendix I. These are:-

- **DC5:** A set of problems ordered based on complexity engages learners in playful exploration.
- **DC7:** Open-ended design problems allow learners to use materials in their ways.

- **DC9:** Open-ended design problems help learners consider failed attempts as opportunities to try new creative approaches.
- **DC11:** Reflections triggered with analogies or questions help learners consider failed attempts as opportunities to try new creative approaches and develop workarounds.
- **DC13:** The availability of just-in-time operational information helps learners remain engaged in the playful exploration and seek meaningful and relevant assistance.
- **DC14:** Reassurances from mentors help learners consider failed attempts as opportunities to try new creative approaches.

We have not found evidence for the following conjectures, and probable reasons have been discussed in section 5.4.4.

- **DC2:** Partial-manipulables assist learners to consider failed attempts as opportunities to try new creative approaches and develop workarounds.
- **DC3:** Partial-manipulable helps learners to express their ideas and emotions with artefacts and actions.
- **DC8:** Open-ended design problems allow learners to express ideas and emotions with artefacts and actions.

Through this set of evidence for the design-based conjectures, we can claim that the features of Tinkery are working as designed. Though challenges emerged with the design of the partial manipulable, the evidence was mixed based on the arrangement of resources, which has been discussed further. On a macro level, when we look at the participants altogether, we also have some process-based findings that we discuss ahead.

5.4 Discussion

In this section, we first discuss the role of the features of Tinkery 1.0 found in our episodes. Then we look at these episodes from a lens of processes to discuss how the features support the problem-solving process. We also discuss the role of prior knowledge of the participants in the problem-solving process. Finally, we close the chapter by discussing the challenges from this DBR cycle to be addressed in the next cycle.

5.4.1 Role of the Features of Tinkery 1.0

The evidence for the design conjectures assures that Tinkery 1.0 can support a tinkering-based approach towards solving engineering design problems. The learners did perform tasks and activities (mediating processes) that pertained to tinkering (Wilkinson et al., 2016). We saw that the partial-manipulables were being used as resources of reference and ideas to some extent, as seen in DC 1. This was based on what experts talk about keeping projects or half-done models visible in the vicinity to get ideas and play with them, which has been termed drawing inspiration in the learning dimensions framework (Petrich et al., 2017). Hence, the partial-manipulable to some extent, played that role. Some prior studies have discussed others' code, or some premade, half made or broken material as a reference for deriving information (Peppler, 2013, 2016; Zaphiris & Ioannou, 2021), which was the case with DC1.

In DC 4, we show and argue the role of the physical arrangement of resources and the ease of search among the materials after making the participants aware of its underlying schema (Martin & Schwartz, 2005), which in our case was Lego's reference cards. The work in the literature suggests using space in a collaborative environment to optimise interaction and collaboration (among participants) (Harris et al., 2017). In contrast, in the current design for resource arrangement in DC4, we see evidence of a process being followed for finding and interacting with resources. We also realised that it was also perceived as an overhead; hence we need to think of the arrangement of tools and resources to enable and support the thinking processes to achieve design (Resnick & Rosenbaum, 2013). This aspect has been further discussed as a challenge.

The ordered set of open-ended problems situated in the physical space allowed participants to explore playfully, per the literature (Harris et al., 2017; Honey & Kanter, 2013). As these problems were in the physical space, we saw evidence of participants building and acting on their built artefacts. Experts have discussed the importance of physicality, the ability to hold and manipulate things to allow them to tinker with them. Literature associates tinkering with manual activities associated with manipulating objects (Baker et al., n.d.) and hence recommends creating an experience that is physical, personal, immersive, creative, sensorial and manual (Harris et al., 2017). By situating the problems in the physical space and association of solution parameters with this physical space we see participants experience the physical aspects, building personal associations with the solution and the design process while immersed in the activities as observed on DC6 & 7. Observations from DC9 show the creative aspect of problem-solving enabled by the ordered set of problems. Hence we could say the ordered set of problems provides a concrete way of achieving experiences that are physical, personal, immersive, creative, sensorial and manual, as well as provide an opportunity for a generative and iterative design that has been talked about in literature (Harris et al., 2017). We discussed some limitations regarding the diversity of the solutions designs in the challenges.

Mentors play a significant and crucial role, especially in the case of problem-solving (Honey & Kanter, 2013). From DC10 to DC15, we have observed that a mentor, through reflections, prompts, just-in-time support and reassurances, has supported the participants' design while keeping its agency with them. The experts mentioned a sense of agency in their design process and their ability to experience and derive from failures and challenges. We observed such instances in the case of DC 10 to DC12. Experts also mentioned scaffolding learners to explore and experience states of failure while mentors provide a safety net from mental or physical harm. We saw in DC 14 and 15 how through mentor support, participants realised and accepted the challenge and then overcame challenges based on their thought processes. In the end, the agency remained with the participants despite some support from the mentor. Literature does recommend creating an atmosphere of play and provisions for requesting and helping (Harris et al., 2017), which has been designed into the role the mentor played through a spectrum of prompts, reflections just in time information etc.

The takeaway from the findings is that Tinkery 1.0, in its version 1, got the participants to behave according to what the experts and the literature said. In addition, its features like the PMs, the various mentor roles etc., specifically for problem design in detail solving problems, have been observed to support tinkering as the problem-solving process of the participants while mating the agency of the solution with the participants. We now look at the narratives with a process lens and discuss findings from observing the process and the participants' behaviours. Further, we discuss prior knowledge's role in the participant's problem-solving approach. We end our discussion with challenges in the current design of Tinkery, which we will address in the next DBR cycle.

5.4.2 Implications of the Findings from a process lens

We looked at the standard processes and behaviours observed among the participants. Based on their impact on the participant behaviour, these were put under the following five broad findings.

- *Learners quickly go from their preliminary idea to building tangible artefacts and frequently use the artefacts to make focused inquiries:* As we saw in the analysis, learners initially, by the design of the environment scaffolded by the mentor, were building solutions that they talk about or the features they have talked about like four wheels, three wheels, autonomy in motion etc. Moreover, until day two, they were being scaffolded to perform actions with tangible artefacts. When actions are being performed on the tangible artefact, we see that inquiry is being made and tends to become more and more focused. As we saw in various examples (Episodes 6.1, 9.1, 9.2, 12.2), when the mentor was nudging them to observe the bot's behaviour, they could gradually focus their inquiry. Interestingly, this behaviour emerges in participants working on the problem in the third session. Here the mentor intervention was minimum in terms of the problem-solving process. It was observed that participants would start with an idea they would want to talk about, then they would build it and observe its behaviour. Based on this behaviour, they would work ahead. Like P1 and P4, when working on the autonomous bot, they would code the colour sensor and observe the action of the bot for each of the codes. Similarly, P3 would focus on how the motor behaves when attached linearly or parallel to the body and make observational comparisons between the two given motors. All these actions and comparisons were being made in the physical on the bots they had built. Additionally, these bots helped them focus on their objective and then get into a broad exploration, like does the colour green in the case of P1 and red in the case of P4 get detected when the bot approaches it and at what distance. Similarly, for P2 on day three does the ultrasonic sensor detect the chair legs or does the proximity sensor do it better? Based on many such episodes, we conclude that the participants quickly built tangible artefacts from their ideas and often used them to focus their inquiry.

- *Learners display agency in their problem-solving:-*

- *They decide/choose to test their conceptual knowledge on the fly based on the feedback they receive when exploring resources or their actions on their built artefacts.*
- *Each learner takes a personalised problem-solving path, changing his/her objectives and solution approach as required.*

Learners have shown significant agency when solving the problems on day 2 and day 3 in their problem-solving process and the evolution of their solutions. As we saw in observation when presenting evidence of DC15, the participants started with the same design as a four-wheel bot and landed on the same problem when trying to turn the bot with just the front two wheels. Nevertheless, their solutions after that are entirely different, and they are of their choosing. P1 chose to explore more and find a solution to balance her bot, as seen in episode 13.1. She had chosen to go with the two-wheel design based on her conceptual knowledge of turning a bot and successfully achieved the solution with a caster wheel. However, P2, on the other hand, based on the actions she performed on the bot, as seen in episode 10.1, can refine her conceptual understanding of turning a bot and using the two diagonally opposite wheels. Hence both resulted in a very different, but even though they were trying to solve the same challenge. On the other hand, P1 and P4 had very similar solutions using two motorised wheels and a dragging caster wheel, but P1's bot was pulling the castor wheel, whereas P4's was pushing the castor as the rear wheels drove it. Moreover, their approaches to programming their bots were very different. P1 uses parallel execution of program blocks whereas P4 uses serial execution using function calls. Code P2, on the other hand, used a set of motor controller blocks controlling two motors from the same code block. In the case of P3 she continuously changes her objectives as the solving progresses like first getting the body of the bot sturdy and then fixing the issue with the wheel while continuing to realise her idea of the bot which is a tricycle design. Her programming approach was simple, using basic single-motor motion blocks. Hence we can observe that all the participants show a strong sense of agency towards their ideas by testing their knowledge as they solve the problem through further exploration or through actions they perform on the artefacts they build. Alternatively, they even change their objectives if their solution path requires them to, but ultimately, it is their own decision. This also brings us to our subsequent findings.

- *Learners persist in realising their objective, by iteratively troubleshooting, developing workarounds, and seeking feedback.* As we observed, all the participants could complete all the problems in one or more ways. They did it based on their ideas and developed them to get to the solution. Through the process, they were troubleshooting challenges, e.g. in the case of P1 and P2 it was turning the bot into problem 2, which they worked around in different ways and completed the tasks. Similarly, P4 determined he wanted to start with an autonomous navigation system, which he spent day two on. He was also faced with getting the bot to stop, but he got to a solution by using two sensors in tandem, as seen in episode 5.1, by using one to turn and the other to stop. P3 was very attached to the idea of a tricycle which she said was inspired by an aeroplane moving on the ground yet she managed to attach a motor to the front wheel and got it to rotate along with two wheels in the end, driving the entire bot with just one motor. Compared to others, she never prioritised placing the EV3 brick on the bot, making her solution different from the other three participants. One important observation here is that the open-ended nature of the problem allowed them to do so, and the mentor's role was crucial, especially in ensuring their participants always had a sense of agency in the problem-solving process. This sense of agency emerges as one of the key factors when working with a tinkering-based approach, as it seems to be the driver of the entire process. This again leads us to our next observation.

- *Learners report a sense of agency and accomplishment with the freedom to set their own goals and take personalised pathways.* Episode 15.1 presents excerpts of conversations the mentor has with the participants. These excerpts commonly report that the participants felt a sense of agency throughout the problem-solving process. Now, they feel confident about working with Lego and any new set they are given. Another question asked to all the participants was, "If they were given a very different set like electronic components that can be used on clothes, how would they approach such a new electronics kit?". The answers varied to some extent. For example, P3 and P4 said they would start connecting things and see how they work, whereas P2 said she would try to make something simple first and then gradually make something of her choice, and P1 said she would probably start with the manual but what she would make would not be just out of the excitement of the new kit. However, she would try to understand how things work and why some things have been connected in a given way. All students said that they would approach this new kit with questions of how and why with everything they do as it will help them better understand the new kit and then they will be able to make things they want to. P2 also mentioned that such an approach would give her ideas for using such different components. We can say that the experience of solving problems with Tinkery has got the participants to think in terms of the components and their ideas.

- *Learners express their abstract ideas in the language of the physical tinkering environment even when physical artefacts are not present:* From day three, all participants were now talking about the Lego components. They would speak of specific pegs when connecting two beams, specify the motor they wanted to use and why, and specifically tell which function of the reflection multisensor and which motor ports they would use to connect it. The participants had internalised the resources and their affordance.

  This was confirmed during the final interview session when the participants were asked to talk about building a pet feeding machine with the Lego kit they had just used. Though there were different ideas for achieving the solution, what was common was their description of the Lego pieces they would use and how. To clarify, during the interview session, they were seated away from the work desk, which had all the Lego pieces; hence they could not see them while they were talking, as seen in Fig. 5.11. So everything they mentioned was in terms of the Lego pieces. P1, P2 and P3 said they would build the body with the frame but P1 said she will connect them with black pegs and P2 and P3 said with blue pegs as it will make it more sturdy. P2 and P4 said they will use a timer to activate a door which is opened with the small motor whereas P3 said she will use a push button to activate the door for which she will use the large motor. P1, P2 and P4 said they would have a sliding door made of beams and driven by a motor and wheels, whereas P3 said she would have a swinging door made of angle beams and driven by the large motor so the extra food could be scooped in. While saying this, they also acted out the motion and how they would connect the pieces. With this, we may confidently claim that the participants had internalised the Lego components and their ability to work with them mentally even when their resources were absent.

Figure 5.11: The interview session. P4 is facing away from the table and acts out this building process for the pet feeder as seen from the observation room.

To conclude, participants built tangible artefacts, which were their bots based on their initial ideas. Initially, it was by the design of Tinkery 1.0, and later they were seen building their ideas on their own. They used these tangible ideas (bots) to make focused inquiry initially scaffolded by the challenge design and later via the mentor and eventually driven by their interest. In building the solution to the problem, they are testing their conceptual knowledge (in the form of their ideas built physically) either based on their exploration of resources or their physical interactions with their bots. These actions are representative of their agency in their personalised problem-solving process. This approach allowed them to change their objectives as and when required. Eventually, they all persisted in realising their solution, helping them build confidence. They also reported a sense of agency and felt accomplished. Lastly, they were able to externalise their ideas by talking in terms of the Lego components. Hence if the learning environments, the pedagogies and mentors encourage and ensure the behaviours mentioned above, they can get the participants to develop a sense of agency. Participant agency in this case, or learner agency in general, is one of the important factors rather than the driver in most instances when considering tinkering-based learning environments or pedagogies.

5.4.3 Role of prior knowledge

The study participants who came from an engineering or a pre-engineering background were all seen tinkering to solve the problems in Tinkery 1.0, irrespective of their prior knowledge. The differences arose with the amount and nature of scaffolding required. Participants with low prior experience in robotics or any such project-based activities, P3 in our case, required more explicit and frequent mentor intervention. Though the mentor intervention reduces with the progression of the challenges, it was relative to the prior experience.

The type of scaffolding varied among participants with low or more mirror experience and knowledge. Participants with low prior experience and knowledge required more nudging and assurances. In contrast, experienced participants were seen to overthink starting with a reasonably complex solution, making it difficult to evolve it structurally and functionally. This can be seen with the variation in the solution between P1 and P2 compared to P3's solutions. P1 and P2 were biassed by their prior experience in a robotics session where they used electronic components to build a four-wheel bot. However, P1 did not clearly remember the concept of making it turn by alternating the direction of motion on opposite wheels. In contrast, P3 started with a very different idea of just using one motor for motion and one for direction as seen on a tricycle.

The participants with some experience in workshops tended to fixate on a design from previous experiences, as with P1 and P2. However, P4, who had more experience working with a similar kit, was not seen fixating. P3 on the other hand, had no prior experience but was inspired by her idea of an aeroplane moving, which she has seen and perceived to realise. Even though P4 had a lot of building and workshop experience and did show variability in approaches and design but at times would abruptly wander among numerous possibilities and had to be nudged by the mentor.

Tinkery 1.0 got the participants to tinker irrespective of their prior knowledge. The difference was in terms of the design of their solutions or the nature or amount of scaffolding that was required. This follows what has been observed in literature regarding the variability in approaches towards solving problems with tinkering (Vossoughi & Bevan, 2014). Our evaluation focused on the evidence of tinkering and not on the creativity, design, or efficiency of the design. One may evolve the participants into any of those directions by eventually adding the criteria as a requirement and or scaffolding them towards it.

5.4.4 Challenges and Implications

Though all the participants were tinkering to solve the given problems, some learning environment features did not perform as expected in the case of DC 2, 3 and 8. We now look into the details of these challenges and try to identify the reasons for finding non-conclusive evidence or not being able to find evidence for all the mentioned conjectures. Following are the challenges that we came across.

1. **Limitation in Exploration:** Participants limited their building resources to a few sets of pieces and participants' initial exploration was limited to the partial-manipulables. Participants generally remain in their comfort zone unless a need arises, or curiosity comes into play through some inspiration or observation of surroundings. During the study, we saw that *P3 was stuck with only using beams for construction and never used frames, and P1 and P2 used frames, beams, pegs and axles but insisted on using only one kind of pegs or used axles where pegs could have been used. P1 mentioned, "There are many pieces I do not know about, but I guess I will just stick to these (pointing at the pieces in front) as I feel I can manage without the different types of pieces; I do not see the need".* Here the participants have discovered a basic set of pieces that were a part of the partial-manipulables, or they discovered with their initial build. They keep focusing on using these sets of pieces in different ways but as long as they feel the need for it they do not explore further. The participants need some inspiration to go beyond their comfort zone. It could be in terms of things they would want to build or if the problems require or even to figure out something in front of them and they feel there is a need for it. Also, partial-manipulables could limit exploration given the ease of access to information on using pieces. However, the partial-manipulables do not use only a few, as the intent was to keep them simple. It was later realised through interviews, as discussed in this chapter, that there is a lack of incentive for the participant to explore the additional components as a requirement for the solutions or as ideas that would require such components. The second problem given on day two was an extension of the first one but just required using other sensors and could have a similar solution design. This problem could have been improved regarding the number of variables one needed to control to achieve a solution. Hence, there were limited solutions, and few cycles of exploration and play were needed

on the third day. The obvious solution was to choose a problem still in the domain of vehicular robotics but raise the complexity by increasing the number of conceptual variables one has to control or balance, increasing the number of possible solutions. Such episodes were counterintuitive to what was intended for by the DC 2 and DC3; hence there is a need to balance simplicity for ease of access and complexity as motivation to explore more in the partial-manipulables.

Current activities did not push some participants to explore the affordance of the programming environment or get them to use extensive materials as a part of their solution. *In many instances, P3 had the opportunity to control her bot via programming, but every time the mentor would prompt her to program, she would try to find a workaround. Later as she did manage to program, her programs were time-based rather than event-based, using sensors. Later she did talk about her inhibition with programming sensors. P1, P2 and P4 used the programming environment extensively but were limited in terms of the components they used. None of them even considered using gers, different types of wheels etc.* There needed to be more confidence in P3 whenever it came to programming. This could be due to her prior lack of programming, which P3 mentioned. The sensor-based activities on day 1 allowed her to connect to the sensor's affordances, but that was not enough for her to develop confidence and explore more programming. Additionally, challenge two, given on day one, did not direct participants to explore the affordance of the programming environment. Hence for such learners, there is a lack of scaffold for needed knowledge and skill or even a small activity in the very beginning among the challenges that require them to program something.

The resource arrangement was not intuitive and required an attention switch, even when using a reference card. *P1, P2 and P3 were seen struggling initially looking for pieces they needed and later avoided exploring other new pieces. They voiced the difficulty of switching from catalogue reference to then the pieces and then figuring out what is placed where. P4 would spend time getting things needed and arranging them in front based on some sense or idea. P2 mentioned, "There are a lot more interesting pieces that I see, but I did not have an opportunity to explore them," the mentor said, "You can go ahead and explore even if you do not feel they would be required, some idea may present to you" to which P2 replies "Ya, but it takes me off the problem and kind of breaks by my* *flow. I know it could give me more ideas, but I think I will go with what I have".* Resource search is in itself a time and mind-intensive task. When participants are tinkering, they only have a limited time and mental faculty to spare. They tend to avoid exploration as it is not a solution-ensuring task but equally intense incredibly if one does not see the intended pieces. This could be due to the absence of ease of access in searching for a required piece, and exploration with new pieces felt like an overhead, especially with a lack of incentive. In most instances, the participants would only refer to the card or explore the trays if necessary. They were comfortable with the components they had become familiar with and would access the tray when they needed more. Any additional exploration that did occur, as we observed with P1 and P3 in some instances, was based on the requirement of the problem or by the intervention of the mentor. Our take is that arrangement of resources is helping the participants, but the way they are being arranged will have to be more intuitive, not requiring the resource card.

2. **Lack of quick experimentation cycles:** Participants did not need/do many exploration play cycles to solve the third problem as there were only a few conceptual design paths to be taken, leading to a similar design. *P1, P2 and P4 addressed the third problem by adding sensors and doing some focused trial and error on the code for the turning radius. There was variation in the conceptual path of solving the problem but not among the solutions. Most of them made a two-wheel/four-wheel bot that used Ultrasonic and Color based detection sensors.* The concepts to deal with here were just sensors, stopping logic and turning radius where some decision must be taken in each of them. Participants did not have to choose among concepts that needed to be applied, just variables that needed to be adjusted, like which sensor to use, use a stop reverse and turn or stop early and turn and speeds at which the wheels move to execute a smooth turn / fast turn or a slow turn. The probable reason could be the third problem's conceptual similarity with the second one, the solution objective needed to be more complex, and there were limited conceptual options available to solve the problem. Here we feel the continuity of the third problem with the larger domain of vehicular robotics needs to be balanced with the complexity of the third problem to allow more variability and challenges.

There was an overhead in time and effort as participants failed to have used the serial monitor. Hence, students need help seeing intermediate states of the solution missing play that could lead to focused inquiry. *P1 and P2 were struggling to estimate the number of rotations of wheels to make it go from A to B. The mentor prompted them to use the serial monitor, and they showed reluctance but then used it, which helped them make a quick and better estimate of the number of rotations. P3 was prompted several times and even guided to refer to a serial monitor to determine the number of rotations. However, she returned to manually counting the rotations every time. When later asked during the interview, she said, "I was not very sure how to use the serial monitor and how it would help me; I was rather ok with just looking at the wheels and counting.".* The participants were taking much time and putting in much effort in doing tasks that allowed them to gain intermediate information necessary for the behaviour of the solution, like the number of times the wheels were turning etc. They keep forgetting or were ignoring or had an inhibition towards using the serial monitor, an essential tool as it allows quick and rough experimentation providing important intermediate information without the need for explicit programming and trying the correct values. The reason varied from forgetting the serial monitor and its affordance, Inhibition in the use of the serial monitor Lack of knowledge.

3. **Fixation, association with domain and similarity among solutions**: Participants get to an initial solution but tend to remain fixated with solution design unless utterly necessary or if the problem requires them to do so. *P1's and P2's second problem four-wheel bot was very similar, and P4's two-wheel and caster wheel design was similar to P1's final design. P3 attempted a three-wheel tricycle design which had some conceptual challenges. Their designs revolved around their initial ideas throughout their problem-solving process. All participants solved their third problem with initial designs by adding a sensor and manipulating the turning, stopping and going by the program.* P1 and P2 had some robotics experience, so they just used the partial-manipulables to work out the connectivity among the pieces. P3 had no prior experience, so her design was based on her inspiration of a quad bike and a tricycle, and then she remained with this design for all the problems. P4 also had prior experience with a four-wheel bot, but P4 worked around the

turning issues in all the problems. A tendency to fixate on the first feasible idea and a lack of opportunity to take different conceptual design paths were felt. All the participants were seen to remain in their comfort zone of the components they were using. The ideas were mainly based on prior knowledge unless a need arose (P3 had to find a new type of beam for her fork) or curiosity came into play (P1 discovered a ball and wanted to use something similar for supporting her bot). Design fixation is a known problem in engineering design literature, and several strategies are used to overcome them (Jansson & Smith, 1991; Purcell & Gero, 1996). There was a lack of incentive or need to redesign further, especially in the third problem. This led to our next challenge.

The same analogy does not work similarly for different people, especially if they do not experience the context in which the analogy is being given. *With P1 and P2, the analogies used to think about steering mechanisms were of how a car steering works and then coming to the concept of centre of rotation where the centre of rotation between the front axles was making the rear wheels skid. P1 did not relate to the analogy as much as she later mentioned she does not drive a car, and P2 did question her approach after the analogy was given. She later figured out that using diagonally opposite wheels would work. For P4, the same analogy was given during a discussion when P4 also mentioned using four wheels and the front 2 to drive. He drove frequently, and when the analogy was given, he said, "Oh, now I get it". P4 then continued the design using a castor wheel. For P3, who had used a 3-wheel design, the analogy was about how an autorickshaw turns. Nevertheless, soon during the conversation, it was realised that P3 associated a three-wheel design with an aircraft and the turning of its nose wheel. She then made the front wheel vertical, and that helped her bot turn.* The analogy of turning a car did not help P1 determine if they just use the front two wheels to turn the rear wheels' drag as the centre of rotation is between the front two wheels. In the case of P2, it did raise doubt in her mind about her logic which eventually helped her. They later reported that they did not know how to drive or paid little attention to the steering mechanism. Though, later, after completing the task, they said the analogy made sense to them now. For P4, the same analogy worked, which was confirmed later by him, and he also knows driving and has conceptual knowledge of the steering mechanism. P3 was able to draw a parallel from the three-wheel auto rickshaw whose wheels are not as visible as that of an aircraft. Though in technicality, the aircraft steers in a different manner than the auto. However, she could abstract the ideas of the vertical column of the landing wheel, making it easier to turn, which is not seen in the case of an autorickshaw. Relatability to the analogy is an essential factor to consider when using analogical reflection prompts.

The challenges discussed have implications for tinkering problem solving by the learners. The limited opportunities in the case of problem two given in session three create a lack of incentive. Lack of ease of finding resources and even limited complexity of the partial-manipulables, which do not implicitly motivate exploration, is further hampered due to lack of incentive. Such limited exploration, in turn, hampers playful experimentation, further restricting curiosity generation (Resnick & Robinson, 2017; Smith & Roopnarine, 2018). The implication is a continuation of random trial and error instead of focused inquiries when stuck in states of uncertainty. Otherwise, it would aid in adjusting goals on the go by allowing learners to construct explanations for the paths they choose to take. Additionally, scaffolds for key-solving strategies like serial monitors hamper the quick cycles of exploration and play; instead, the learners spend much time in estimation, calculation and complete system trials to get the variable and their values right. These challenges and how these could be addressed, along with the objective of more evidence and a better understanding, are the objectives of our next DBR cycle (cycle 2), discussed further in the next chapter.

5.4.5 Conclusion of DBR Cycle 1

Based on the evidence for 12 out of the 15 design conjectures, features of Tinkery 1.0 support tinkering as per the requirements defined in the literature for evaluating tinkering. This conclusion was made based on the design conjectures framed using the conjecture mapping technique (Sandoval, 2014). The evidence for the conjectures came from the analysis of the interactions using methods of interaction analysis (Jordan & Henderson, 1995). Moreover, the behavioural observations made later also support tinkering based on the nature of activities performed by the participants. We also concluded that learner agency (in our case, the participants' agency) in the problem-solving process is a significant factor. It is the driver of their problem-solving and a motivating factor in keeping them engaged. Hence attention to the design of the elements of the environment in which learners tinker is critical in allowing them enough freedom to take their problem-solving paths. Secondly, the mentor's role was crucial as they must ensure a sense of agency with the learner. We concluded that it was possible to do so based on the guidelines for the mentors in Tinkery 1.0. However, some challenges have emerged, which we will address in our next cycle and refine our conjectures. Also, in DBR 2, we look for evidence to support the theoretical conjectures further to strengthen our claim that learners tinker to solve engineering design problems in Tinkery 2.0.

Chapter 6

DBR2: Modification and Evaluations of Tinkery 2.0

In the previous chapters, 4 and 5, we discussed conceptualising and designing Tinkery 1.0 using the design conjectures. Then we described our study to determine if our design conjectures hold. The findings from the study revealed that most features of Tinkery 1.0 could support a tinkering-based approach to problem-solving and also revealed certain challenges. Additionally, we gained insights into the processes when participants tinker to solve problems. In DBR cycle two, we aim to address the challenges and make relevant changes to the design of our learning environment. To evaluate our redesign, we conducted another study with the new version of our learning environment, Tinkery 2.0. We present the evidence for the new and modified design conjectures and provide evidence for the theoretical conjectures. Additionally, we investigate further into the processes of problem-solving with tinkering.

6.1 Need for changes in LE design and guidelines

One solution for encouraging exploration is to provide incentives by including partial-manipulables that demonstrate the use of complex pieces as well as making it inspiring learners to try and use components in similar ways. This is based on the experts' behaviours discussed in Chapter 4. Experts keep all sorts of projects around them: simple as well as complex, and finished as well as unfinished in their surroundings, irrespective of their relevance to the current task. This was reported to be a source of inspiration. Research suggests that the arrangement of resources in the environment should be based on some of their underlying characteristics or hierarchy (Brahms & Werner, 2013). The characteristics could be visual or functional. As in our case of vehicular robotics the learners primarily depend on the functional characteristics so we chose to arrange the resources as per the functional characteristics.

Important resources that provide insight into a process have been considered key in performing focused and quick inquiries expressed by the experts, as discussed in Chapter 4. Hence it becomes essential to highlight the importance of such resources in ways that their capabilities are understood. One of the ways could be to demonstrate them in context with an example (Resnick & Robinson, 2017). In addition, keeping such resources in students' working memory could be explored, like mentor-based prompts or nudges. Further, learners should at least be provided with references to examples built with the resources, irrespective of their relevance to the current problem.

One of the ways to force learners to think further than their ideas is by providing problems that require multiple concepts and, in turn, several variables to control to come to a solution (Linsey et al., 2010). Secondly, by choosing the second problem so that it does remain in the same context but does require the learners to switch, the solution approach may break their design fixation carried from the first problem (Viswanathan et al., 2014). Finally, explicitly introducing such resources and doing demos of the use of affordances of the resources can encourage learners out of their comfort zone of components and experiment with more of them (Viswanathan & Linsey, 2013). Conversely, analogies are context and experience-specific (Hesse & Klecha, 1990). Hence in case analogies have to be used as reflection triggers, it would be recommended to situate them in a context that the learner is familiar with. A summary of the challenges, the underlying reasons identified, and the redesigns have been presented in Table 6.1.

Table 6.1: Summary of challenges and the corresponding design changes to address them.

No.	Challenge	Reasons	Redesign
1.	Limited Exploration	Simple Partial-Manipulables	Partial-Manupliables with variable complexity
		Lack of incentive from problem	Complex Problem 2 with many conceptual variables
		Non-intuitive resource arrangement	Arrangements based on functional affordance
2.	Lack of Quick experimental play cycles.	Limited exposure to port view	Demo of port view in the context of problems
		Limited exposure to using the programming environment.	Demo of programming environment in the context of problems
3.	Fixation & association with a base	Similarity and limited complexity of problems 1 and 2.	Complex Problem 2 with many conceptual variables

	domain		Introduce and allow the use of the manual as a repository of ideas.

Based on the discussion mentioned above, there was a need to change how the partial-manipulables were designed by varying them in complexity and adding some association to the domain in which the learners would be working. Requiring the initial challenges to not only make learners explore various components and their affordances but also make them use these affordances to build something tangible and requiring the second problem to have more than two conceptual and decision variables, breaking continuity from problem one while remaining in the same domain as of problem one and arranging the resources based on their function as the problems require the solutions to achieve a functional requirement hence making the arrangement more intuitive. Introduce learners to key features like the serial monitors (in the case of Lego known as the port view) with demos that emphasise their capability. Similarly, providing demos for tasks that seem complex based on situated examples to ease the learners into using them like the programming environment. Even demo complex concepts that the learners may need to get more familiar with—finally providing learners access to a repository of examples built using the resources which in the case of Tinkery 1.0 is Lego Mindstorms. Based on the challenges mentioned above, we referred to our observations from the experts and literature for redesigning certain features of Tinkery 1.0 to Tinkery 2.0.

6.2 Tinkery 2.0

Most of the design of Tinkery 2.0 remained the same: the pedagogy, the Lego Mindstorm kit and its resources remained as they were in Tinkery 1.0. The role of the mentor is similar, apart from a few new prompts that were introduced. Challenge one and challenge three given on day one were observed to help get the learners started. They focused on introducing the ultrasonic sensor and getting them to build a simple, functional model that worked well; hence they were kept as is. The problem given on day one was also kept as it provided enough complexity to get the learners started with cycles of exploration and play. Scaffolds in the form of partial manipulable were continued but the manipulable were changed. Resources were also rearranged, though there were specific changes in how they were arranged. The details of the changes made and their basis are discussed as follows:-

- **Problems:** To ensure a gradual increase in complexity literature recommended increasing the number of key variables to deal with (Honey & Kanter, 2013; Sheridan et al., 2014). Also one can frame the problem in such a way that allows multiple applicability of multiple concepts (Sheridan et al., 2014). We here qualify the word "complexity" by defining the number of concepts required to solve a problem and the number of variables one may choose to control to reach a solution. Choosing concepts and control variables will lead to numerous possibilities in solution approaches and the solution itself. Hence, we can now define the gradual change in the complexity of the problems as an increase in the number of concepts and variables that must be balanced to derive a solution.

  Hence the second open-ended problem now is complex enough to force learners to switch contexts from the first problem. A problem in the continuation of linear motion was chosen, requiring more conceptual knowledge about the motion of vehicles on an incline. The new problem required more numbers of variables to be chosen from and controlled, making it relatively complex and allowing more varied possibilities. Further to ensure the learners can understand the use of a resource affordance, one may give problems that require their discovery and use them to make something tangible (Resnick & Robinson, 2017). Hence challenge two was extended by having the learners to program the reflection sensor to produce an output on the brick screen. The changes made are as follows:-

  Challenge two for day one: At the beginning of the session on day one during the introduction session a demo of a simple program is given in, which demonstrates how to draw a facial expression on the controller screen from the programming environment. In continuation of challenge two which has the colour detection activity, the participants are required to change expressions on the controller screen when a different colour is detected leaving the choice of colour and corresponding expression to the learners. Hence, they need to implement colour detection that shows how it can be performed.

  Problem two for session three: Problem two that is provided on the third day requires the learners to make a bot cross an obstacle and then climb an incline to stop on a platform. Participants must decide among the wheelbase (length of the bot between the front and back wheels), ground clearance, powered wheels, power train, suspension or a combination of these. Further, they have to deal with multiple variables within each of these conceptual paths. E.g. if they choose to go with the gear train and which and how many gears to use and where they should be added, if they choose to modify the ground clearance then it could be done by varying the wheel size / the axle height / even the chassis design. Hence each aspect they choose has many other variables to deal with, which are sometimes interdependent, like the wheel size impacts the chaise height and the traction when climbing an inclined. The objective of moving up rather than moving from A to B on a plane is still in the larger domain of linear motion on a plane. Moreover, problem two now requires the usage of bent beams, various pegs, gears and a variety of wheels and axles.

Figure 6.1: The new problem requires the participants to get their bot to get on the try, climb the inclined tray and get off on the box and stop.

- **Resource Arrangement:** Literature on scaffolding suggests alignment towards semantics of domain (Quintana et al., 2005), which in our case is robotics with Lego Mindstorms. Hence functional properties of the components were chosen as semantic bases on which the resources were classified and arranged (Brahms & Werner, 2013). Based on the observations from DBR 1 and the literature, we concluded that the resources should be arranged based on the discipline's semantics and the learning environment's objective. I.e. For solving problems that require the solution to achieve a function, one could primarily segregate the resources functionally and later arrange them based on the structural characteristics. In contrast, when the solution objective is better aesthetic, then the resources may be segregated based on their structural characteristics and then arranged as per their function or a sub-classification based on specific physical characteristics like colour or shape. Such an intuitive arrangement may allow an efficient search and allow learners to understand their affordances and possible uses just by looking at how the resources have been arranged. The new arrangement of the blocks is discussed as follows:-

The spatial arrangement of Lego blocks: The basis of the arrangement is now the broad functional affordance of the Lego components. The resources were arranged by classifying them into building components, connectors, motion components, decorative components, sensors, actuators, and bricks. These align better with the semantics of robotics with Lego Mindstorms (Quintana et al., 2005) and are consistent with scaffolding exploration and encouraging play. Further classification amongst the significant classes was done based on the visual characteristic of the form of the components. Further during the introduction an explicit mention of resource arrangement as per function and then further over form is explicitly done to make the learners aware of the mechanism. A similar mention of programming block categories based on their underlying functional affordances is also made when introducing the programming environment.

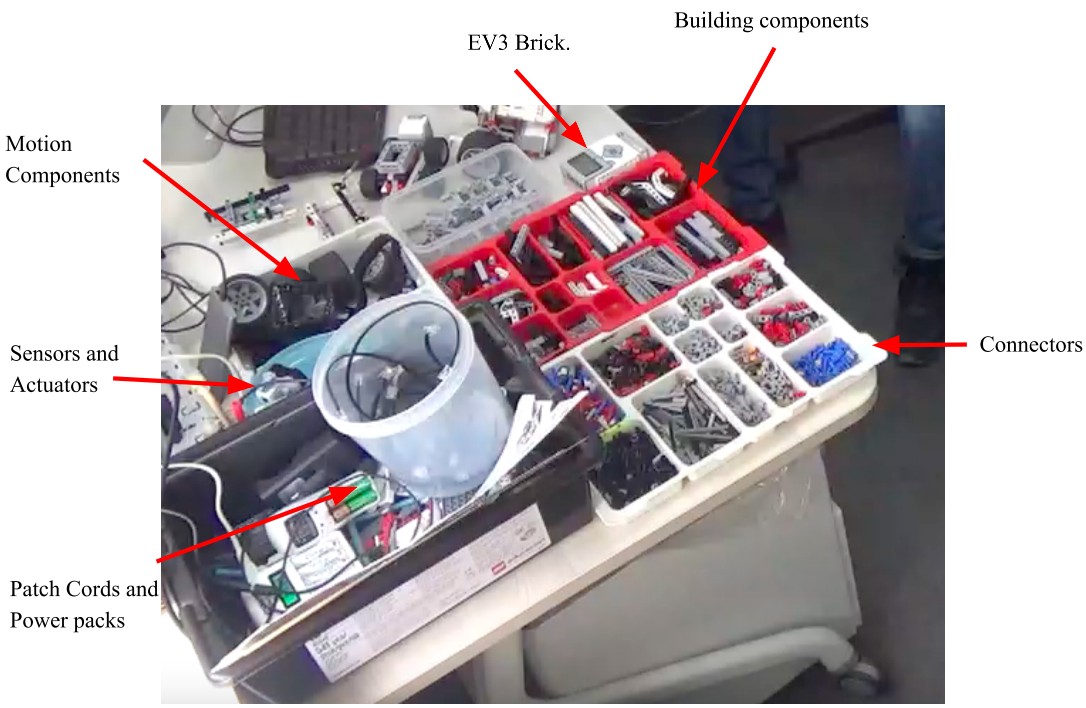


Figure 6.2: Spatial arrangement of Lego components primarily based on functional characteristics.

- **Scaffolds:** Based on the previous observations, an additional suggestion is to use a wide variety of materials to solve the problems and have them built in an order of complexity like a very basic construction that is easy to replicate along with complex examples that use several specialised parts. The aim is to make it easy for the learners to replicate the easy one and build curiosity with the complex ones to motivate themselves learners to make more inquiries. In the case of partial-manipulables which act as a scaffold, apart from a wide variety of components that were relevant to the problems were used and the models (partial-manipulables) themselves were made relevant to the domain of the problems. The manipulable were built varying in complexity from examples that use simple connections to models with the implementation of complex gear mechanisms allowing a wide variety of possibilities.

Additionally, essential tools and techniques while working with a set of resources should be demoed with an example so the learners understand their needs and how to use them. Demos of components or other resources situated in the context of the problems or the domain in which the problem has been given also allow learners to understand their usage and build association (Blikstein, 2013; Viswanathan et al., 2014). Providing enough example solutions to similar problems could help overcome design fixation (Viswanathan & Linsey, 2013). Hence several explicit demos, like serial monitors and resources that provided examples of bots available with Lego's online programming environment, were also explicitly introduced, and learners were encouraged to refer to them. Analogical reflection prompts must be aligned to learners' experience; hence, alignment will help them understand the conveyed ideas (Goswami et al., 1998; Hesse & Klecha, 1990). The initial demos should be simple and easy to follow but should be able to emphasise the need for such a tool or technique. This can also be done for some critical concepts by doing demos and making the learners reflect through techniques like predicting, observing and then explaining. The changes discussed above have been implemented as follows: -

Partial-Manipulables: Partial-Manipulables ranged from simple to complex where simple was a basic chassis assembly with frames and wheels, the second one was a steering mechanism example using two independent axles and a rake a pinion gear system, and the third and most complex was a gear assembly of the differential gear system and some high and low gears connected to two wheels. These partial manipulable are not just examples of the use of resources but also inspirations that could be reengineered to derive solutions to the given problems. The chassis and steering mechanism were relevant examples to solving challenge three, problems one and two. In contrast, the differential gear assembly was a complex but inspirational example relevant to problems one and two.

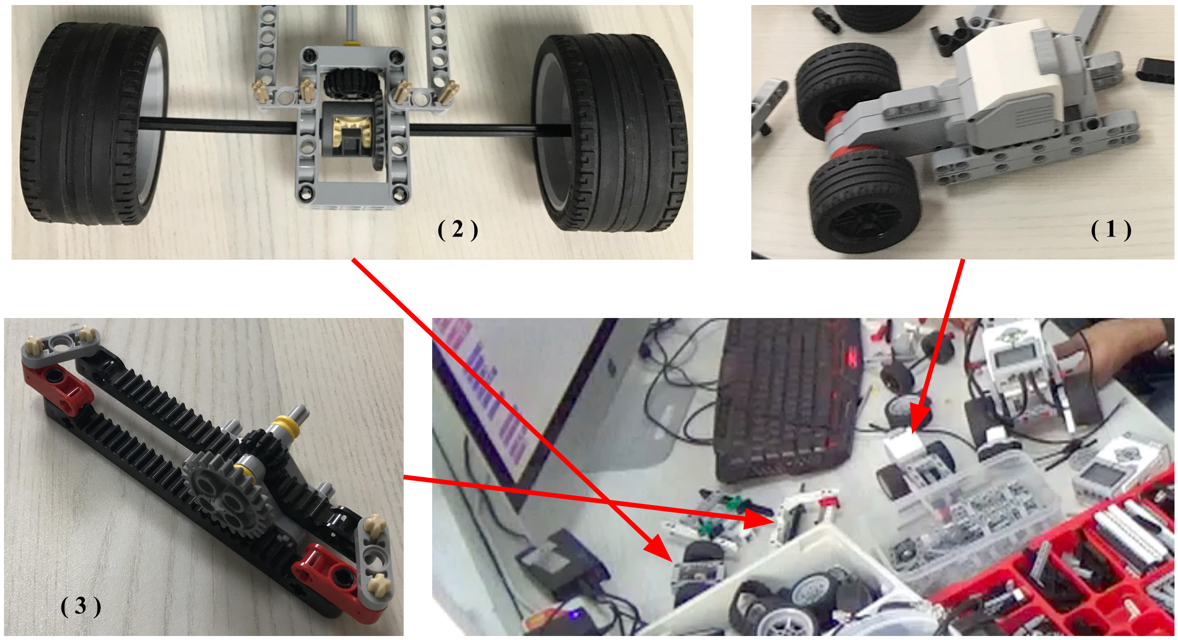


Figure 6.3: Partial manipulables displayed kept on the working desk. 1) Motor wheel assembly, 2) Rake and pinion steering & 3) A wheel differential gear assembly

Serial Monitor Demo: Explicitly introduce a serial monitor on the controller in the programming environment (Screenshots in writing) by clicking the brick and showing how changes on the brick can be seen on the screen. Provide mentor prompts to use the serial monitor as a question. Demo to and show changes in state on a serial monitor when using a touch/switch sensor.

Introduction to manual and sample models: Introduction to models in the manual that align with motion-based problems with the freedom to pursue them. Explicitly show various models during the introduction and prompt about them when a need for ideas is felt.

Additional mentor prompts: For the problem, one analogy can depend on their experience with driving, or seeing a tank based on the participant's experience. Form problem 2 Analogies can be from experience of gears if riding bicycles and experience in riding/driving vehicles in lower vs higher gear. When participants show conduction by comparing parameters to test their idea, prompt them to pick an aspect/concept/variable and test the idea. Ask what and why questions on the action and prompt to stick to one concept/variable at a time till a response has been formed.

Table 6.2 Summary of changes made in Tinkery 2.0.

Redesign	**Changes made**
Partial-Manupliables with variable complexity	We changed two partial-manipulables, one an example of a rake and pinion steering mechanism and the other of a differential.
Complex Problem 2 with many conceptual variables	The second problem requires participants to decide between ground clearance, wheel-based, number of wheels, drive mechanism and the chassis structure.
Arrangements based on functional affordance	The resources are now arranged as building components, connecting components, Motion components, Sensors, and cables.
Demo of port view in the context of problems	An explicit demo and an example of using the port view feature during the initial introduction was was included
Demo of programming environment in the context of problems	An explicit demo and an example of using the programming environment during the initial introduction were included
Introduce and allow the use of manual as a repository of ideas	Manuals were introduced as a repository to take inspiration from in the introduction session.

To summarise, Tinkery 2.0 has a new challenge that requires learners to code the EV3 brick to detect the colour and draw a face on the brick screen. A new problem requires the learner to mount on a platform by getting over some bumps and climbing up to the platform. The resources are now arranged as per their functional characteristics to make the search intuitive as per the requirement. Three new partial-manipulables vary in complexity and component usage. On the first day, the use of port view (serial monitor) and the programming environment is demonstrated, and learners are explicitly shown a repository with a number of sample models along with instructions that the learners are free to use.

Based on this redesign and introduction of demos, changes were made to the conjectures in terms of the addition of embodiments which resulted in the formation of new and modification of a few old design conjectures for whom the evidence needed to be more substantial. In addition to the design conjectures, we present the theoretical conjectures for Tinkery 2.0, which will be evaluated in the study conducted in DBR cycle 2. Evidence provided for the design conjectures will establish the ability of the features of Tinkery 2.0 to generate and support the mediating process of tinkering, and the evidence provided for the theoretical conjectures will establish the nurturing of the cognitive, behavioural and affective outcomes observed in tinkerers as mentioned in the literature (Petrich et al., 2017). The new (> DC15) and revised (marked as DC x`) set of design conjectures is as follows: -

DC 2`: Partial-manipulables that vary in complexity offer learners opportunities to take multiple approaches to solve the problems.

DC 3`: Partial manipulable allows learners to express their ideas and emotions as artefacts and their actions.

DC 4`: Access to resources displayed according to their functional characteristics supports learners in performing actions on built artefacts to seek feedback and use materials in their ways.

DC 8`: Open-ended problems with multiple possible outcomes allow learners to express ideas and emotions with artefacts and actions.

DC 16: Providing demos of programming in the programming environment allows learners to engage in playful exploration.

DC 17: Providing demos of using port view and motor controller allows learners to perform actions on built artefacts to seek feedback and troubleshoot iteratively.

The set of theoretical conjectures (**TC**) is as follows: -

TC 1: Learners engage in playful exploration, perform actions on built artefacts to seek feedback, troubleshoot iteratively and develop workarounds to persist through challenges to meet solution requirements.

TC 2: Learners engage in playful exploration, use materials in their ways, take multiple approaches to solve problems and ask for meaningful and relevant assistance to build conceptual understanding of the domain.

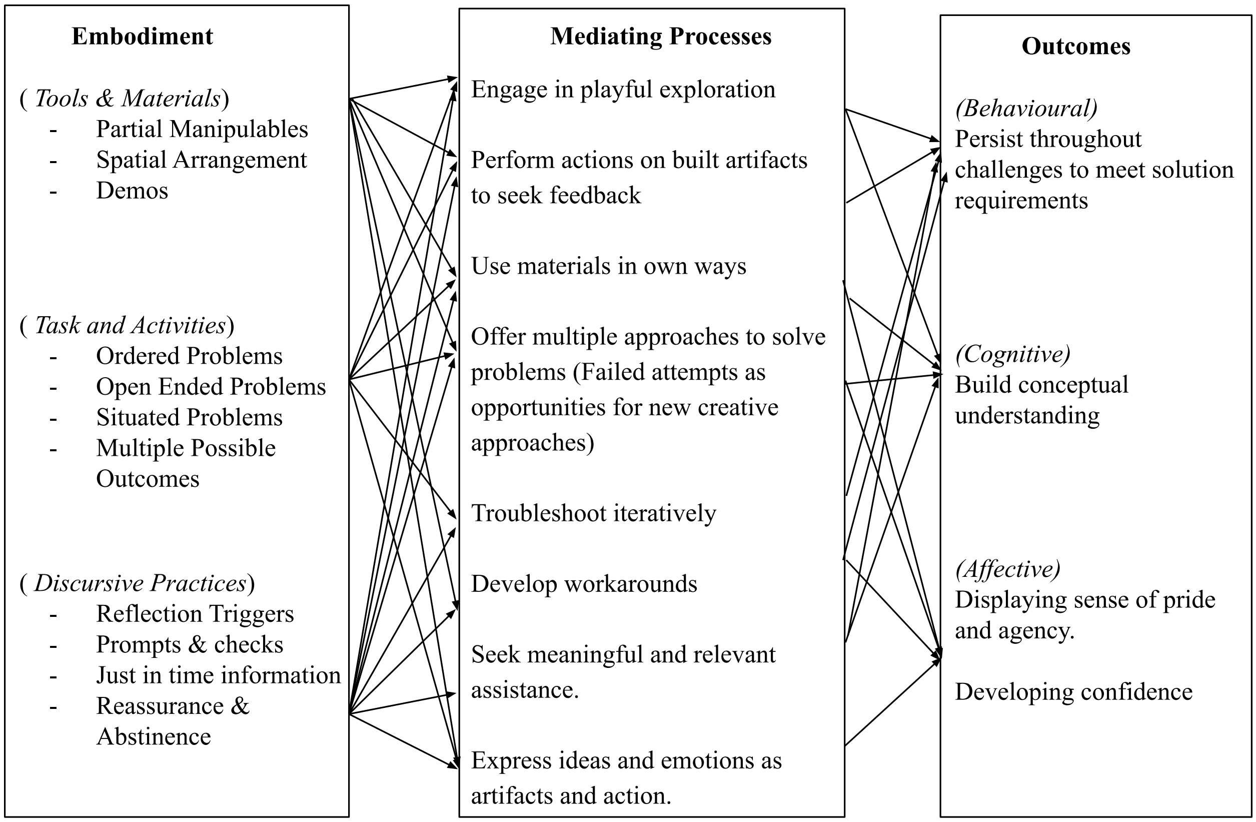


Figure 6.4 Conjecture map of Tinkery 2.0 in DBR 2.

TC 3: Learners use materials in their ways and express ideas and emotions with artefacts and actions to display a sense of pride and agency in their solutions and problem-solving process.

TC 4: Learners take multiple approaches to solve problems, use materials in their own ways and develop workarounds to develop confidence in their problem-solving process.

As mentioned earlier, they are based on the redesign of Tinkery 2.0. The theoretical conjectures are based on explorations, expert data and literature on the tinkering-based activities' evaluation. These were evaluated by providing evidence from the study conducted in the second DBR cycle discussed in this chapter's subsequent sections.

6.3 Study design

With the given changes in Tinkery 2.0, the design and theoretical conjectures to be evaluated in a second study were designed to help us answer our broad research questions:

RQ1: What features and activities should a learning environment have to nurture tinkering?

RQ2: How does the learning environment lead the learners to tinker?

For RQ1, we focus on understanding how the changes in Tinkery 2.0 overcame previous challenges while learners tinker to solve given problems, which is answered by providing evidence for the revised design conjectures. In contrast, RQ2 is answered by providing evidence for the theoretical conjectures. In addition to evaluating the conjectures, we also examine emergent problem-solving behaviours. Most of the study design is the same as in DBR-1 and as seen in Fig. 6.5.

On day one, the learners were introduced to the Tinkery with explicit mention of the spatial arrangement, a small demo of the serial monitor and the programming environment in about 10 minutes. The learners are free to ask any doubts. After that the learners are given the three challenges with the new Challenge 2: Use the Lego brick with any sensor to sense a given set of colour pieces and use them to program expressions on the Lego brick screen. (30 mins). This day is followed by a Reflection on the session (15 mins), and the second day remains the same as in study 1. If the learner can complete the problem and has time to spare, they may even attempt obstacle avoidance.

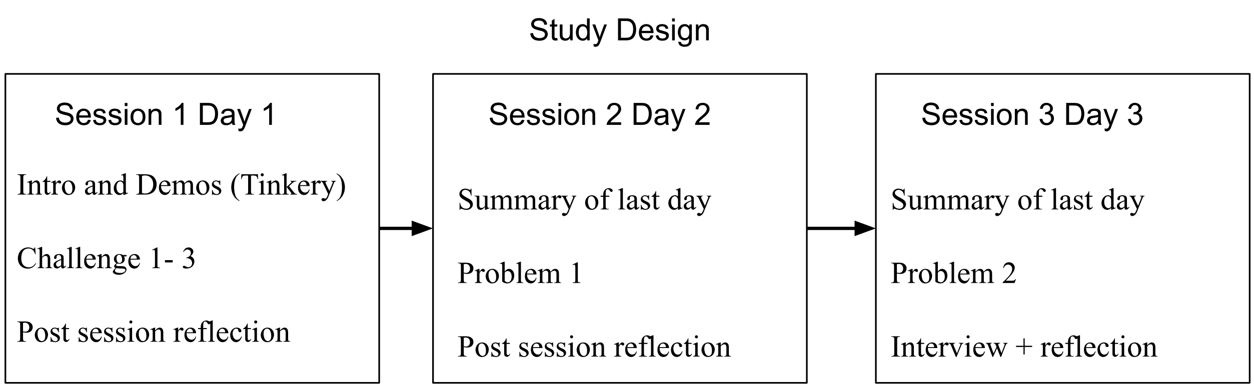


Figure 6.5: Study design for every participant.

On the third day session three the learners start with their experience from the previous day. Then they are given a new second problem to solve in 2:30 hours. The problem now requires them to build a bot to cross a bump-like obstacle to reach an inclined plane. Then climb the inclined plane and reach the platform at the end of the inclined plane. Once the learners have been able to perform the task or time gets over, the learner gives a post-session reflection followed by an interview which is a stimulated recall-based interview on their problem-solving process. The interview ends with a hypothetical problem of making a pet feeding machine which they have to explain how they will build with the resources available. This study was also advertised as a workshop for Engineering Design Problem solving with Lego Mind-storms. However, this advertisement was shared among a local engineering college and a few people from our research lab. A total of 12 participants had registered, out of which two were unable to come as per the required time slots, and two later did not come to participate due to personal reasons and urgent engagements; hence a total of 8 participants completed the workshop. The participants were a mix between second and third-year mechanical and electronics undergraduates. Most of them had some prior experience working with robotics but not specifically Lego Mindstorms. All participants came individually in each session for a total of three sessions done in three days. The workshop lasted for over a month.

Like DBR 1, Video Data was used to understand the interactions with the resources and the resources they use to build the solution. Observation Logs were used to mark episodes of interest or log questions for the interviews. The interview logs were used to analyse the participants' perceptions or triangulate observations made by the researchers. In addition, a hypothetical problem was given to the participants to be solved, for which they had to think aloud and talk about how they would solve it and what the solution would be like. Videos were recorded from the table top and a side view to capture the actions performed by the learners in the entire space. The side view camera was kept in the observation room, as shown in the previous study, to reduce the number of cameras in the visual field of the learners. Additionally, the Mac was recording the screen, and the inbuilt Facetime camera was recording. The Facetime camera was being used as a non-intrusive backup camera. The post-session interview was also recorded in video and audio. This was to gather evidence of learners showing indicators or mediating processes suggestive of tinkering and reflect on how learners use ideas and resources. In DBR 2, we also had a researcher observe the mentor and the learner from the observation room, logging the interactions between the mentor and the learners while listening to the conversations in the room over an intercom between the observation and the study room. Additionally, the mentor, the researcher, had a handheld camera to record any specific moment that he felt was important.

The choice of analysis method for DBR 2 is also interaction analysis, as the objective was to determine how learners, through their interactions with the features of Tinkery 2.0, tend to tinker to solve engineering design problems. Various interactions at play are physically observable and act as the mediating processes for the design conjectures. For the 8 participants over three days, we had 24 sessions of three hours each to be analysed. The analysis was done as similarly as done in DBR 1.

1. First pass of videos to identify episodes of interactions with designed features that changed and actions they perform with their constructions, leaving other episodes.
2. In the second pass, we write a narrative for a few after sorting, merging and finalising the episodes based on relevance to RQs or something interesting that emerges. After the second pass that resulted in a rejection of a few explodes and the merging of others.
3. Interpreted the episodes from the lens of tinkering-based interactions.
4. These narratives were then used to gather evidence for design conjectures.
5. These narratives also provided some emergent findings when analysed with the process's lens, focusing on epistemic and pragmatic actions.

We have primarily referred to the narratives from the third day, as our focus was to present evidence supporting the design conjectures. The other narratives have been referred to for evidence and triangulation of our findings in support of the theoretical conjectures. The evidence also suggests a few process-based insights, which have also been discussed.

6.4 Findings

Snippets from the narratives discussed above were used to identify supporting evidence for the conjectures. These snippets are termed as Episodes below and provide evidence for the conjectures. We discuss details of 3 conjectures from the redesign to give evidence. The rest of the new design conjectures have been discussed in Appendix II. Additionally, for each conjecture, many similar episodes across participants' narratives account as evidence, but we present a few representative episodes as evidence. A summary of findings for all the design conjectures has been discussed at the end of this section.

6.4.1 Evidence for Design Conjectures

- **DC 2`:** Partial-manipulables that vary in complexity offer learners opportunities to take multiple approaches to solve the problems.

In the following episode, participant one tries to solve challenge three: building a bot that can move forward, reverse and take turns. He was seen playing with the differential Partial-manipulables in the beginning. He started with four wheels on a frame then moved to 6 wheels but later started with a single motor and two wheels but cannot build something that satisfies the requirement for challenge 3. Continuing the next day, he can build a bot that solves challenge 3 and problem 2.

Episodes: *Participant was given challenge three to make a bot that moves forward, backward and takes a turn. The participant started to play with the differential partial manipulable. He looked at it and was rotating one wheel while observing the other wheels. Then he keeps the differential and starts connecting other frames. . . . . He is seen connecting the frame that had the wheel to another frame which is similar making it look like a chassis that has four wheels. He continues to add more wheels and now one frame has four wheels and the other one has two hence a total of 6 wheels. He then starts moving the frame front and back and as the other frame is connected with the just beams he is able to lift and move it freely. As he continues to keep observing, moving and playing with the wheels, the mentor asks "So what have you built here?". The Participant replies "I was trying something but now I am trying to figure out where to add the motor and how it will turn?" and goes back to observing and then says "I guess I will use the motor to mount the wheels and then figure out the turning". He removes the wheels and now adds the wheels to the motors and tries to build a frame and attach two beams at an angle. He then says "I am trying to build a bike like a bot" and continues to build it. . . . .(He tries figuring out how to connect the front wheel but by then the time for day one is over). . . As he closes for day one he is seen playing with the rake and pinion PM.*

On Day 2 Participant 1 has to complete challenge two from day three and also work on problem 1 for day 2. His half bot from day one is kept as it is. He picks that bot and dismantles it. He seems to be taking a new approach as he kept the rake and pinion PM along with him. . . . .(he continues to build using the rake and pinion PM modifying it to fit his designed bot). . . . . .. He now attaches the independent axles on the rake and pinion and is seen playing with the mechanism as he moves one wheel with the hand observing the movement of the other. Observing this the mentor asks "Is this working *as intended? What are you trying to figure out?" to which he replies "Yes, I am trying to figure out how and where to connect the motor to make it work" to which the mentor replies "ok, continue". . . . . (As the front of his bot takes shape he is seen working on the rear two wheels) . . . . . . .He then picks up the differential assembly PM and starts changing the axles. He attached a bigger set and then started to work on the addition of the differential to the rest of the chassis. The mentor then asks "Why are you using this assembly?" to which the participant replies "To make sure the vehicle turns smoothly when we turn the front wheels" . . . . .*

Fig. 6.6 shows the progression of the challenge and how the partial-manipulables were referred to. They were incorporated into P1's solution. The last bot can be seen in Fig. 6.7, where the same bot has been used to solve the challenges of day two and day three. The participant made minor changes, like removing the tyre at times, but the basic solution remained the same.

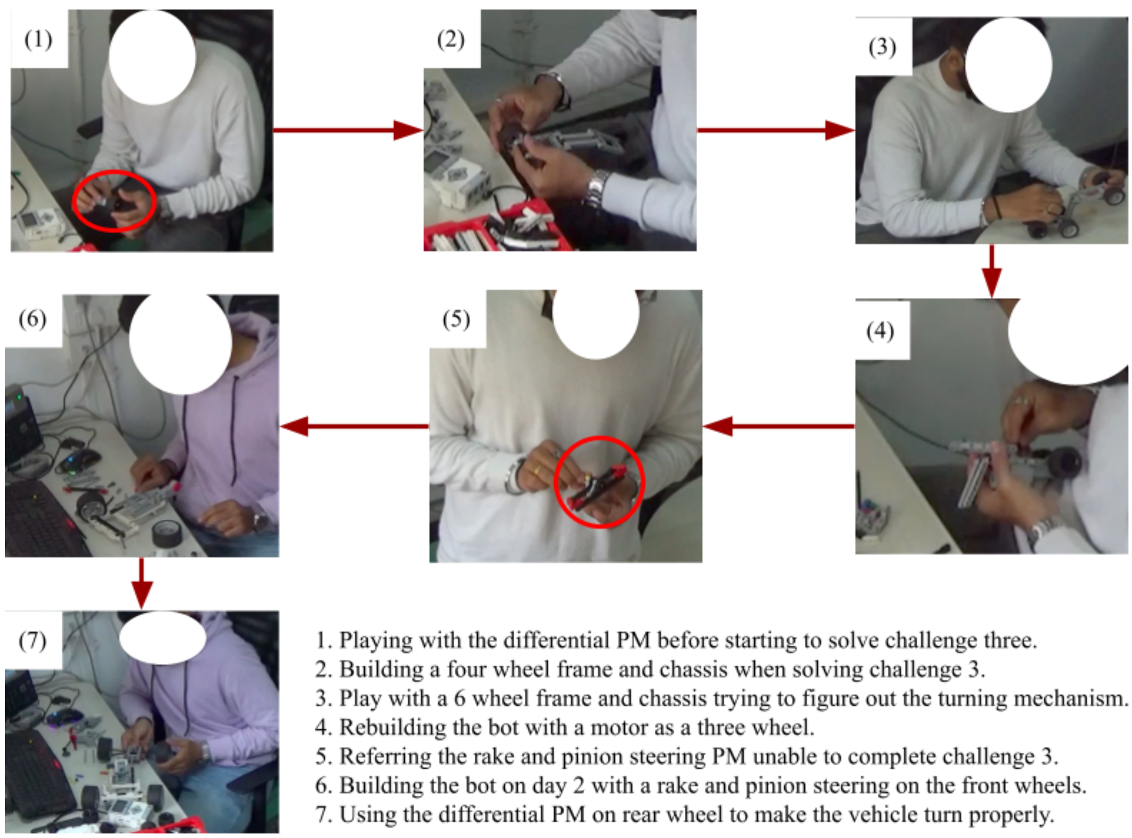


Figure 6.6: P1's solution progression in reference to the partial manipulables (PM).

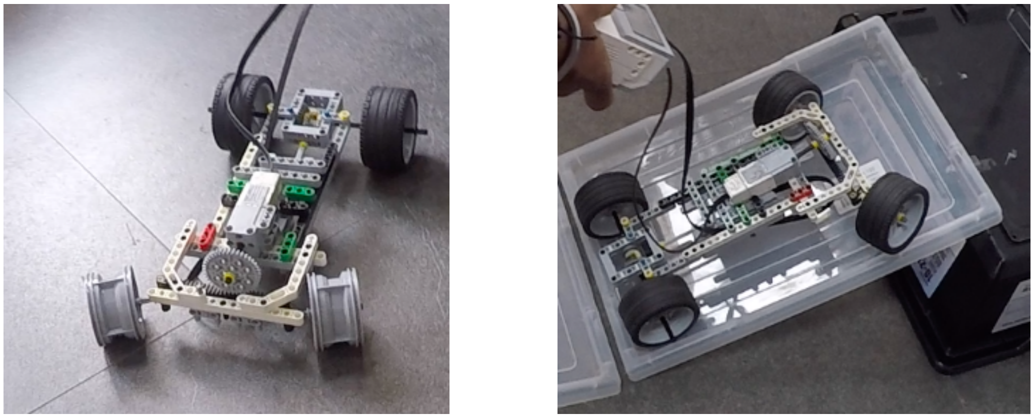
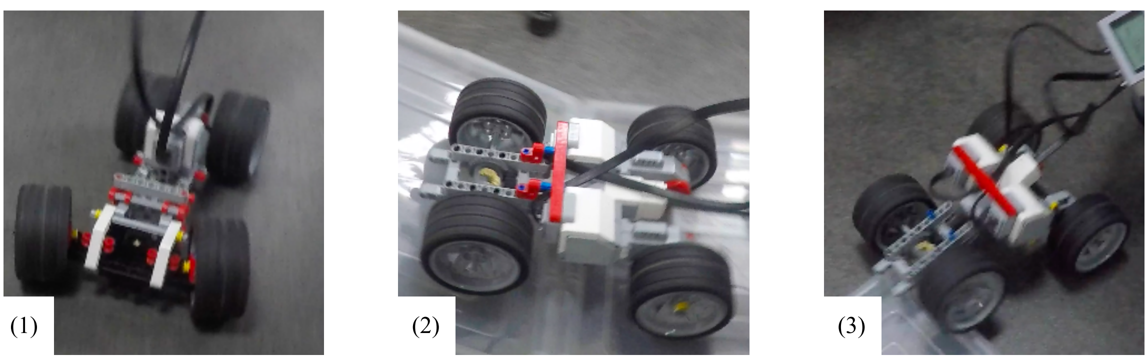


Figure 6.7: Same bot designed by P1 for both the problems with minor changes like tyres.

Another example is presented in Fig. 6.8 of Participant 6, where he has built two bots, one for problem one and the other for problem 2. The rake and pinion PM were used without differential in solving a problem on day 2. The differential has been used on the front wheels for bot two, built as the solution to problem two on day three but did not use the rake and pinion mechanism for problem 2. Among the solutions of day three, we see in Fig. 6.8(2) and 6.8(3) there is a change in the chassis design, which has been built at an angle compared to being built flat.



Participant 6:-

1. Solution for problem 1 using the rake and pinion steering but no differential on the rear.

2. Solution for problem 2 using a differential on front wheels.

3. Solution (2) modified with an angular chassis to avoid obstacles.

4. Two different bots with two different approaches for problem 1 and problem 2.

Figure 6.8 : Solutions designed by participant 6 based on the PM for problems 2 and 3.

We see that Participant 1 and Participant 6 have modelled their solution around partial-manipulables. Later they mentioned in the interview that the partial-manipulables helped them release the solution ideas. The partial-manipulables have been used differently and in different ways by both participants. P1 used the partial manipulable to overcome challenges as he faced them, whereas P6 used them initially for ideation. As we see in the episode, participant 1 had been exploring the partial-manipulables rite from the beginning as he is seen playing with the differential PM in Fig. 6.6.(1). Initially, he does not use it. He tries to make a 4 to 6-wheel bot where he faces the challenge of how he would turn the bot Fig. 6.6(2) &(3). He then changes to a bike-like bot seen in Fig. 6.6 (4), which he cannot finish on day 1. Before wrapping up day one, he is again seen playing with the rake and pinion PM, and the next day he is seen building a model that has both the rake and pinion steering mechanisms and the differential in his solution. During the interview, he mentioned referring to the rack and pinion-based mechanism and then attempting to use it and design the bot since he was not able to Fig. out how to mount motors on the bike-like model he was attempting. Here we see that the PM allowed him to change his design process by allowing him to experiment with the steering mechanism to give him enough confidence to use it. Once he had successfully used it, he was also confident about using the differential.

Whereas in the case of P6, he was seen referring to both PMs right from the beginning. He starts solving problem 1 with the rack and pinion PM as the steering mechanism to turn the bot, as seen in Fig. 6.8 (1). For problem two, he is seen playing with the differential right from the beginning and also asks the mentor about it as he was confused about the opposite motion of wheels when the wheels are being turned with hands. As the mentor tells him about the differential, he first attaches a motor and then uses that to make his first model seen in Fig. 6.8 (2). Later, based on his trials for solving the problem modifies the flat chain of the bot, as seen in Fig. 6.8 (2), to an angular chassis to overcome the obstacles at the beginning and the end of the incline, as seen in Fig. 6.8 (3). When asked about using the differential, he said he wanted to build a vehicle with power on all the wheels but did not want to use something other than four motors. He wanted rear wheels powered with the high-power motor and the front ones also powered but distributed with the differential. He chose the low-power motor as its movement is linear, making it easy to use with the differential. We understand that even he used the differential, but it was not out of a challenge he faced but was based on his interest in using them to make the bot. Both P1 and P6 designed very different solutions where the angular chassis of P6 was a very creative way of increasing the ground clearance of his bout without increasing the height of the wheel mounts.

As for others, participants 4 and 5 considered the partial-manipulables to figure out their working and used the chassis as the base to realise their solutions. Participants 3 and 8 referred to the partial-manipulables as a reference to how to use and connect components. At certain stages tried considering using the partial-manipulables but did not use them entirely in the end. Participants 2 and 7 did refer to the partial-manipulables to build an understanding of the complex pieces but only used these references during the building. The partial manipulable did aid the understanding of the complex components like using gears, combining them with axles, and mounting them on frames, as reported by the participants during the interviews. Based on the variations amongst the solutions, especially for day three, it could be said that the majority of the participants were able to develop some understanding of component use as is or to derive or even refine their solution ideas. Hence we can conclude that the partial-manipulables allowed the participants to discover the affordance and use of basic and complex components. The use of the components depends on the solution ideas and approach the participants take. In some cases, we have observed that these partial-manipulables have helped participants generate ideas and build their solution paths. Hence they helped participants by allowing them to take multiple and, at times, creative approaches to building and solving the problems.

- **DC 3`:** Partial-manipulables allow learners to express their ideas and emotions with artefacts and actions.

  &
- **DC 8`:** Open-ended problems with multiple possible outcomes allow learners to express ideas and emotions with artefacts and actions.

The idea of these conjectures is that the participants should be able to express their ideas through artefacts and their emotions like confidence and curiosity through actions like experimenting, taking a risk and acceptance. So the problem would need to be open-ended with multiple possible outcomes. Also, the partial-manipulables could aid the problem-solving process by allowing the participants to realise their ideas in the physical or perform actions with them to do so.

Here the change from DBR1 was the problem; precisely, problem three now allows multiple possible outcomes as it could be solved by controlling a set of variables of the participant's choice. Secondly, the participants were made aware of the manual and were allowed to use the manual to solve the problems. The manual has instructions for building a bot that can be used to solve problem 2, but one would still need to program it. There is no immediate solution for problem 3. Another thing to note is that as this was an independent study, the participants came in different sessions which did not overlap. Also, the numbering of the participants is random and not in the sequence in which they completed the sessions.

In the following episodes, the solutions of all the participants for both problems have been presented, and the variations observed in their solution approach strategy have also been presented. Also, the role of partial-manipulables has been present in the progression of their solution either as a part of their ideas or the solution itself.

Episodes: *For problem one and two participant 1 after a lot of trials referred to and used the rack and pinion mechanism PM by attaching wheels. Initially he was using the big motor to control the rack and pinion which he later changed to the small motor. He chose to manage the drive train by powering all wheels with three motors and the differential which he referred to from the PM. Moreover he chose to use the largest size wheels to increase the ground clearance and build a long wheel base to allow the bot to climb better. He used the same model for both the problems with a few minor modifications like removing two tyres from the wheels in case of problem one. To program the bot for problem 1 he just used single motor control blocks as he just had two motors that could be controlled sequentially.*

Participant 2 followed the manual to build a two wheel bot with a castor wheel to solve problem 1. To program the bot he used the move block with a number of rotations at *specified speed to control both the motors simultaneously. For problem 2 basically he modified his initial design of the castor wheels with motorised wheels. He chose to manage the drive train by using three motors to power the four wheels, two individually and one with a common axle and used the largest set of wheels on the bot for a better ground clearance. Though he was seen experimenting with the differential PM he never used it. He also added a pair of non-powered small wheels at the centre to be able to overcome an obstacle. After a demo of the gearing mechanisms he just used a combination and was able to help him solve the problem.*

Participant 3 like P2 followed the manual to solve problem 1 but later also added sensors to make the bot autonomous. To program the bot he also used the move block with a number of rotations at specified speed but in a loop to control both the motors simultaneously. For problem 2 like P2 he modified his bot from problem 1 and used one additional motor to power two wheels with a common axle but the structure of his bot varied from that of P1 with a better ground clearance as he used less structural components. He did refer to the frame and wheels PM while adding the rear motor and wheels. Additionally he did not use any gears even after the demo as he was able to complete the challenge without them.

Participant 4 like P2 and P3 followed the manual to come up with a solution for problem 1 but her bot did vary a bit structurally as she used smaller wheels and the beams in the front. To program the bot she used a combination of move blocks with a number of rotations at specified speed and also degree of rotation and direction with a number of wait blocks in between to control both the motors simultaneously. For problem two chose to start with a combination of the chassis and wheel manipulable along with her solution from problem 1. She gradually changed the chassis by experimenting with it and modifying the two wheel design to a four wheel design. In her final solution she used four wheels powered by four independent motors. Even she was seen to refer to the frame and wheels PM when before she choose to go with all four independent motors and wheel.

Participant 5 also used the manual to solve for problem 1 but later made a few modifications and also used the sensor to make his bot autonomous. To program the bot he also used the move block with a number of rotations in a given direction to control both the motors simultaneously. For problem 2 his solution was similar to the previous *participants with four wheels and four motors. Though he started with the bare minimum possible vehicle built out of the chassis and based on its trials he evolved the design like adding two more wheels, then using bigger wheels, then increasing the wheelbase and mounting the brick on the back top to make it rear heavy. He was not seen referring to the PMs though he did play with the differential once which he confirmed during the interview later.*

Participant 6 for problem 2 was seen experimenting with various gearing options to drive the rack and pinion. He had referred to the rack pinion PM and incorporated it. He just used a big motor with two rear wheels on a common axle to drive his bot. To program the bot he just used single motor control blocks as he just had two motors that could be controlled sequentially and experimented with the number of degrees of the motor to get the turning radius right for the bot to go from A to B. For problem 2 on day three he was experimenting with the differential manipulable by attaching a bigger wheel and a motor and using the motor controller to see how it behaved. Through these experiments he later mounted the other two motors for the wheels on the other side of the buggy making a four wheel three motor bot design. With further trial to climb he modified the linear chassis frame to an angular frame allowing him to overcome the obstacle on the top of the incline. He chose to design two completely different bots for both the problems without using the principles from one into the other.

Participant 7 also followed the manual to solve problem one but she used a small wheel set like P4. To program the bot she used a combination of single motor blocks to make it turn and move blocks to make the bot go forward. For problem 2 on day three she was seen to experiment with the frame and wheel based manipulable. She built her bot with just one motor connected to two wheels with a common axle and two non-powered push wheels in the front. Later she looked at the manual for a reference to used gears and tried a combination. After the demo of gears she changed the gear combination to produce the maximum torque making the bot slow but powerful enough to climb up. In the end the chassis got stuck at the top obstacle as the rear wheels lost contact with the incline which she was not able to fix.

Participant 8 initially referred to the manual to solve for problem one but stopped using it half way and made a functionally similar but structurally different bot as *compared to the manual. To program the bot she used a combination of move blocks with a number of rotations at specified speed and also move blocks with degree of rotation and direction to control both the motors simultaneously. For problem 2 on day 3 she followed the same solution path and designed the same solution as P7 but after the gears demo she chose to use the same gears but inverted to what P7 did making her bot very fast. She used this speed to gain enough momentum to be able to climb and jump over the obstacles.*

As we observe in Fig. 6.9, the solutions for problem one, apart from P1 and P6, all other participants had a similar solution functionally. However, it varied structurally to some extent for P4 and P7 but a lot for P8. Here we see that all these six participants chose to accept the manual as a place to start, followed the same instruction, and incorporated their choices in designing their solutions, leading to minor changes. P1 and P6 built their solution from scratch based on their ideas and experiments and took risks using complex pieces like a differential and the rack and pinion steering system. This shows that even though the problem could be solved with the given solution, it gave participants the choice of how they wanted to start. The problem also allowed them to change their earlier chosen path like P8 did or still incorporate some unique ideas in the solution, as seen in the minor variations of P4, P7 and others. Additionally, a similar observation has been made in the case of the programs written as part of solving problem one, shown in Fig. 6.10.

Problem 2 is an entirely different story where all the bots vary structurally and functionally. P1 and P6 used differential systems and three motors to power four wheels, but both had varied chassis designs. P1 got to his design by referring to the manipulable when he was stuck, whereas P6 incorporated them into his solutions from the beginning. In this case, we also see the impact of the partial-manipulables on how they choose to express their ideas and perform their actions. P2, P3, P4 and P4 started with their bot from problem one but modified it differently where P2 and P3 used three motors, two to power two independent wheels and one to power two wheels on a standard axel whereas P4 and P5 chose to use four motors and four wheels. Among them, their solutions varied structurally. P7 and P8 used similar solutions structurally, whereas functionally, they were the opposite, where one relied on a gear ratio to produce high torque and the other relied on the opposite gear ratio to use high speed to gain momentum. Hence we see here that the participants use their ideas to influence their physical design and then take actions based on their emotions, where P1 and P6 took the risk of using a differential creatively, P2, P3, P4 and P5 performed actions on their old bot to evolve a solution for the new problem and P7 took a confident approach of using a high torque to climb where a for same structure P8 choose to take a risk with high speed to jump the obstacles and gain enough momentum.

Hence problem 2 allowed all the participants to choose how they wanted to solve the problems and build their ideas as per their understanding of the physical. They express their confidence, curiosity and excitement, as reported during the interviews with actions like experimentation, taking risks, accepting conflicts, and working with them. Based on these episodes for both problems, we can claim that in Tinkery, open-ended problems allow multiple solutions not only to allow participants to use materials in what they want but also to give them this opportunity to express their ideas as physical artefacts and express their emotions through actions.

Regarding the partial-manipulables, we observe that the participants refer to the manipulable but use it differently as they surely draw attention initially by generating some curiosity. Some experiment with the manipulable to use it, and some draw ideas from the experimentation or use it as a reference. We also observed participants who just addressed their curiosity by playing with them but did not use them or refer to them in their solution approach. A single participant may also exhibit all or some of the behaviours mentioned above based on the problem, the stage of their solution or the solution approach. One thing we can claim is that partial-manipulables allow them to perform personalised inquiry by becoming a means to experiment with or derive from one's ideas aiding the process of building the ideas into the physical and allowing actions based on their emotions.

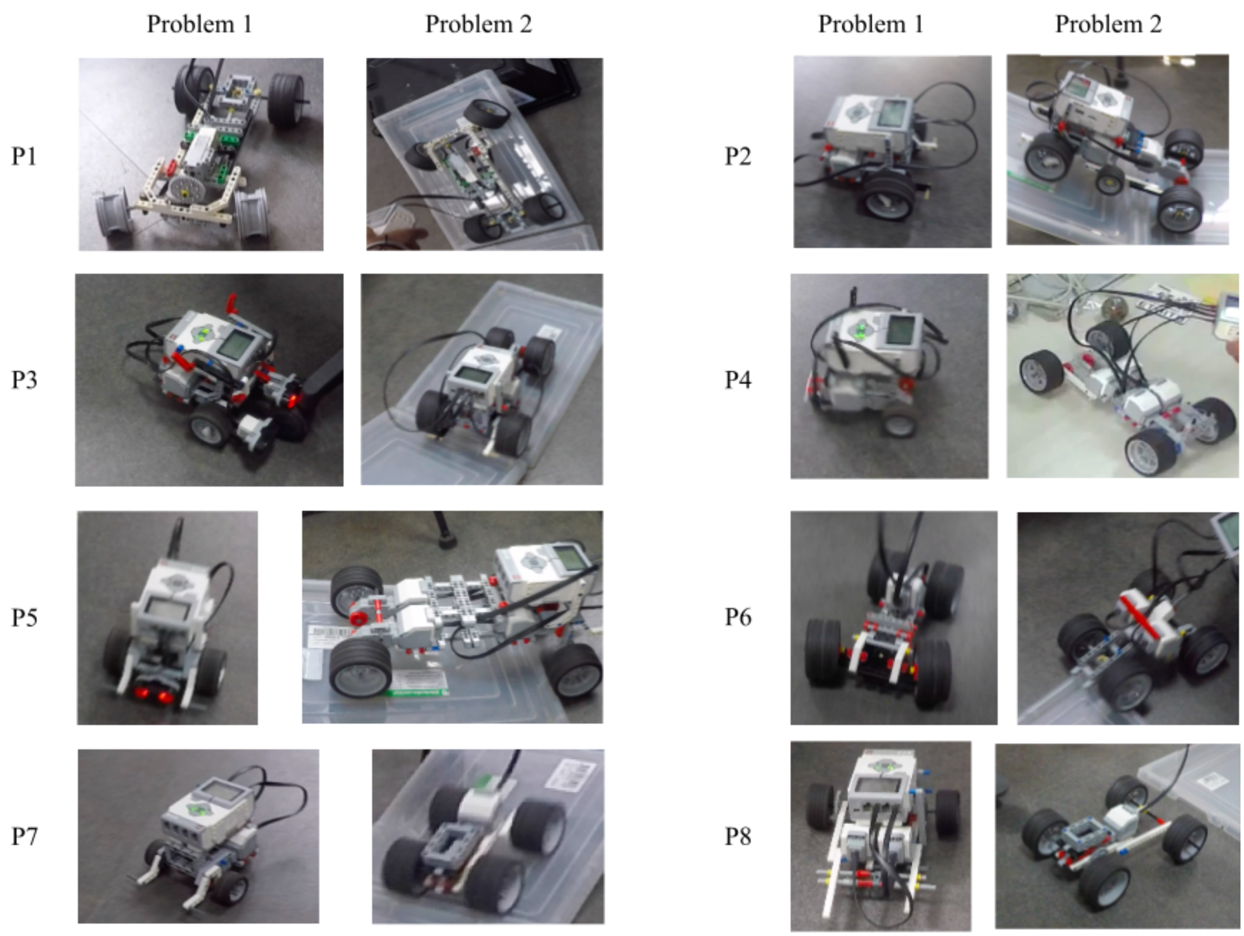


Figure 6.9: Bots built by participants as solutions for problem one and problem 2 for the DBR 2 study.

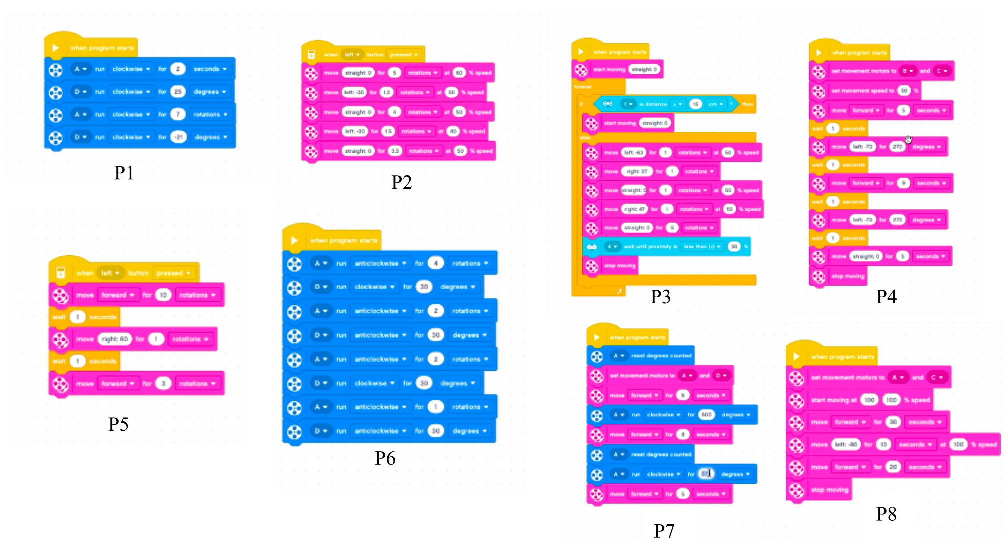


Figure 6.10: Code by participants for their bots to solve problem 1 for the DBR 2 study.

Apart from the episodes of conjectures discussed above (DC 2`, 3` and 8`), we have discussed some additional episodes in Appendix I. We also found evidence for the following conjectures, which have also been discussed in Appendix I. These are:-

- **DC 4`:** Access to resources displayed according to their functional characteristics supports learners in performing actions on built artefacts to seek feedback and use materials in their ways.
- **DC 16:** Providing programming demos in the programming environment allows learners to engage in playful exploration.
- **DC 17:** Providing demos of using port view and motor controller allows learners to perform actions on built artefacts to seek feedback and troubleshoot iteratively.

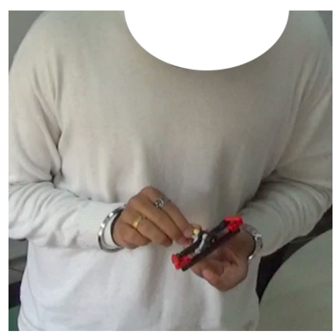
Through this set of evidence for the design-based conjectures, we can claim that the modified features of Tinkery 2.0 are assisting as designed to support the processes that helped participants tinker. Now we look at the theoretical conjectures to establish that the participant's observed processes while solving problems in Tinkery 2.0 suggest tinkering being used to solve these problems.

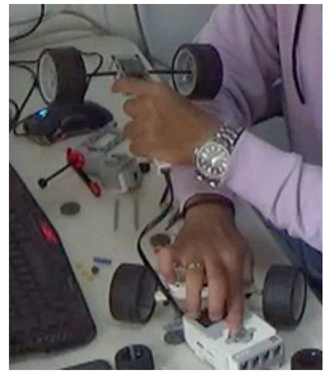
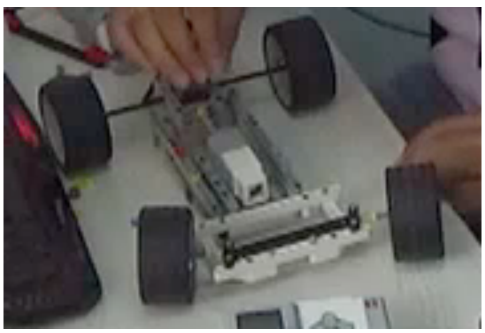
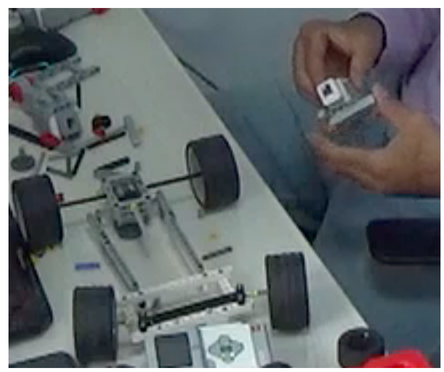
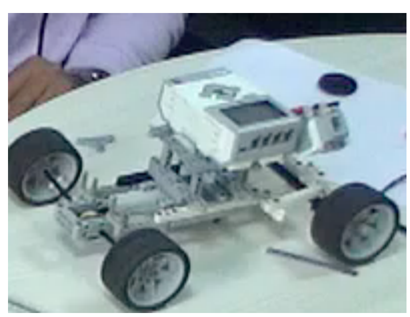
6.4.2 Evidence for Theoretical Conjectures

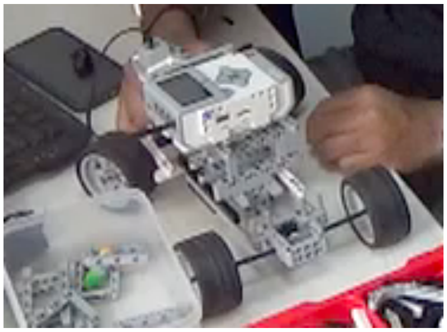
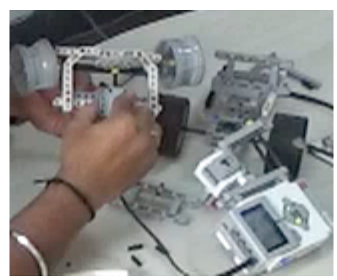
TC 1: Learners engage in playful exploration, perform actions on built artefacts to seek feedback, troubleshoot iteratively and develop workarounds to persist through challenges to meet solution requirements.

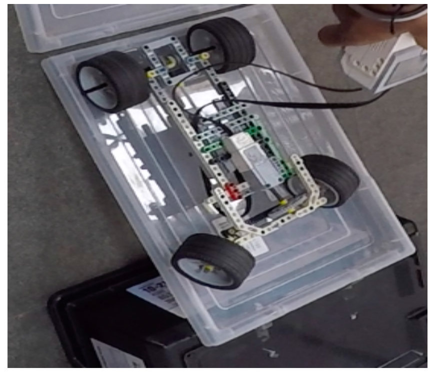
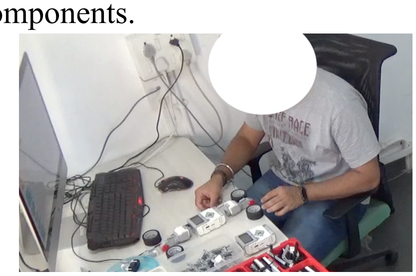
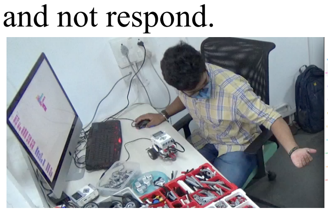
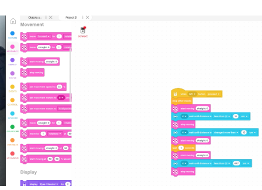
In the previous sections, we presented evidence for the embodiments of Tinkery 2.0 supporting the mediating processes. For this conjecture, we have playful exploration, performing actions on built artefacts to seek feedback, troubleshooting iteratively and developing workarounds as the mediating processes. These processes helped the participants overcome the challenges they faced while solving the problems in Tinkery 2.0. We present evidence from various participants in the form of challenges faced and the actions taken by the participants governed by the mediating processes to persist through those challenges. The choice of participation is based on maximum variation (heterogeneity) sampling (Patton, 2014), where the participants have chosen two varied methods to persist when broadly classified. Also, we observed that the same processes led the participants to persist in two different ways hence based on the theoretical replication logic (Yin, 2017) for the same outcome in two varied ways, we chose to present evidence of Participant 1 and Participant 5.

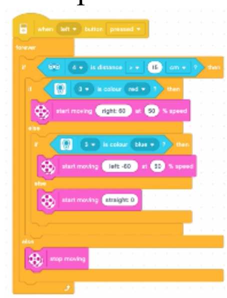
Episodes:

Challenge	Participant Actions
Participant 1	
Getting the bot with six wheels to move and turn. 	*Experimented* with the six-wheel design and *worked around* it by changing his idea to build a bike-like bot. 
Mounting the front wheel on the bot like a bike. 	*He worked around* it by *exploring and playing* with the rack and pinion PM and *changing his idea* to use that mechanism for steering the bot. 
Deciding the gear and motor to use for the rake and pinion. 	*Explored* multiple gears, made multiple trials, and *based on the feedback* in terms of gear size and motion, chose the gear and tried again. Use the large motor mounted vertically. 

Powering the rear wheels 	*Played with the differential PM* and powered it with a small motor. With a *few trials* tried to mount it on the bot. 
Unable to mount the rear differential motor in the current design. 	*Experimented* with components, redesigned the bot chassis based on beams, and used frames as a platform to mount the motor. 
Vertical mounting of the steering motor as the motor being used provides orthogonal rotation. 	*I explored* many components by attaching them and trying to figure out a way of *mounting the motor,* and finally used the EV brick to mount the motor. 

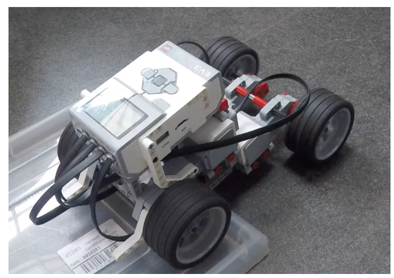
<table>
<tr><td>The wheels are not turning, and the steering gear tends to slip.
</td><td>After many trials and observations, he found out the tyres were causing the wheel to resist turning. So he removed the rubber tire and just kept the plastic wheel.
</td></tr>
<tr><td>The steering motor is too bulky and hence not stably attached.
</td><td>He tried many variations for connections and several other components to stabilise the motor and then experimented with another smaller motor. He finally used that motor to steer.
</td></tr>
<tr><td>Programming the bot to go from A to B.
</td><td>Explored the blocks and used a simple motor block to control two motors linearly. He ran a number of trials to figure out the exact values of rotations of the motor to go from A to B.
</td></tr>
</table>

Get the bot to climb the incline. 	Added the rubber wheel back to increase grip. The bot had enough ground clearance. Tried several long runs to gain momentum to get the bot to climb. 
Outcome: Playing with the PMs allowed P1 to evolve the idea of his solution. Through iterative actions on his built bot and addressing the feedback he receives on these actions he can identify and address challenges by using materials in his way and varying the ideas as and when required. Ultimately, he can solve both problems by implementing minor variations in his bot. Hence, the participant persevered to solve the problems in his own way changing his ideas twice and building and then redesigning to build it again till he felt the problem solutions were achieved. This way, he persevered to build a solution the way he wanted from scratch.	
Participant 5	
Building a bot that can move forward and backwards and take turns for problems 1. He has ideas for which he can be seen arranging the components. 	He initially tries to build a bot based on his own idea and tries to make connections then *works around* by using the manual. Follow the manual to construct the bot to solve problem 1.  
He was trying to code the bot to move after removing the obstacle as it would just stop and not respond.  	*Playfully explores* several different control blocks. *Performs trials* with these blocks and, based on the *feedback,* evolves the code in some *iterations.*

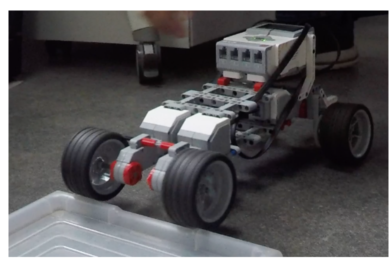
	 With some reflection questions from the mentor and *exploring* loops and conditionals, he got the sensor to monitor continuously. He was able to develop a code to get the bot to respond. 
Getting the bot to climb the initial obstacle onto the flat tray.  	Playfully explores several options like treads with small wheels, but they keep coming out.  Tries skis with larger wheels, but the skis lift the wheels, making them lose traction.  Through these iterations of playful exploration and the feedback from actions made on the bot, he tries a four-motor and

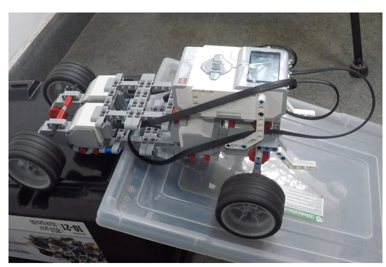
four-wheeled design using two motors at the back. The non-sturdy design makes the motors come off.

He changes the connections to make them sturdy. This also gets stuck due to low ground clearance.

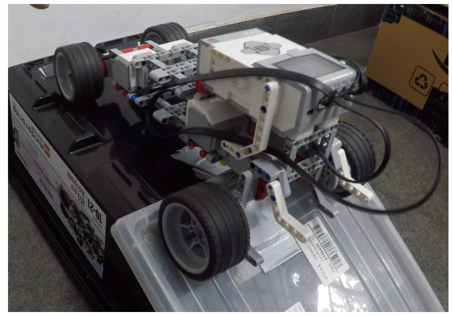


Based on all the playful explorations and interactive trials, he changes the design and builds a new bot. This one gets stuck at the obstacle on the top.





With a minor redesign of his bot, he can overcome the challenge and climb to the platform's top. This way, he can build the bot and get it on the platform.

<table>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Outcomes: P5, unlike P1, choose to use the manual to solve the first problem. This could be his workaround for figuring out all the bot's components and design. However, he used this manual to develop an understanding of the components and their use. The same applies to programming, as he playfully explores the blocks by loading them on the bot and executing the commands to see how the block responds. As he continues doing this iteratively, he can get to a solution that meets the requirement. Similarly, for problem two on day three, with many playful exploration and action cycles, he can get the bot to climb the incline and reach the platform addressing one challenge at a time.</td></tr>
</table>

Previously we had seen that when participants were supported by the various features (embodiments) of Tinkery 2.0, they performed actions governed by the mediating processes, which has been discussed extensively in the design conjectures. In the observations above, what we see is when the participants are seen following processes of playful exploration like P1 explores the various gear combinations, he can determine the correct choice of gear and what problem he persisted through. When stuck with the idea of the bike, he plays with the PM performing actions to understand its functionality. He is seen considering it and changing his idea of a solution working around the challenge of figuring out the front wheel mount for his bike-like bot idea. He also ran many trials to determine the correct values for the code to get his bot from A to B troubleshooting iteratively. Finally, with all the processes supported by the various features of Tinkery 2.0, he can design a solution that not only meets the requirements but can do so based on his ideas and understanding of the components and the domain that he has developed. Similarly, other participants like P5 encounter different challenges, develop their ways of overcoming them and are finally able to build a solution which again is something based on their ideas and understanding of components and domain.

Based on the above discussion, it is evident that the set of processes followed by the participants led them to overcome the challenge and persist until they reached the solution. This is irrespective of any other incentive as the participants were assured a certificate and food irrespective of whether they completed the problem or not and were given these before the interviews were conducted. Here the only possible drivers of intrinsic motivation were the opportunity to solve the problems with Lego Mindstorms, which participants stated also has been presented in the episodes for **TC3** and **TC4**.

TC 2: Learners engage in playful exploration, use materials in their ways, take multiple approaches to solve problems and ask for meaningful and relevant assistance to build conceptual understanding of the domain.

For this conjecture, we have playful exploration, using materials in their ways, taking multiple approaches to solving problems and asking for meaningful and relevant assistance as the mediating processes. These processes helped the participants build a conceptual understanding of not just Lego and its components but also vehicular robotics to some extent, as demonstrated by them in solving the problem and even reported by them during the post-session interview. We present evidence from various participants as episodes that demonstrate the gain of conceptual knowledge and what they say about the gain of conceptual knowledge in the interview.

Episodes:

Conceptual Understanding	***Process***
Participant 2, Participant 3 and Participant 5	
Concept: Sensors have limitations in sensitivity.	Challenge one was designed to run them into the limitation of the ultrasonic sensor. All participants initially gave a wrong estimate of the room's dimensions. Through observation, they realised their estimates were wrong as the reported length and breadth were similar, which was not the case. They all *played* with the senor in different ways to realise this limitation. Later they corrected their estimates and verified them by doing the calculations in *multiple ways*.
Finding: Through the process of playing with sensors, the participants were able to understand that the sensors have limitations. When they coded the sensors later in problem one, they were seen performing actions to find the sensitivity and accounting for it, which was visible in the code.	
Participant 7 and Participant 8	
Gear Ratios for power vs speed.	Both the participants did *seek assistance* from the mentor to understand *how gears helped*. During

	the interview, they mentioned they did know gears could help but did not know how. The participants gave them a demo of how gear combinations change the torque and speed. They implemented the gear ratios as per their requirement P7 (torque) and P8 (speed), which allowed their robots to climb the incline
Outcome: During the interview, when questioned about what gear combinations they would use on a bicycle when going up vs down they explained lower gears for going up with higher torque and higher when coming down to get more speed. Through seeking assistance and observing the demos, the participants could choose gear combinations per their requirements and apply them to their bots. Later they were able to explain the concept using bicycles as examples.	
Participant 1	
Parallel vs perpendicular motion delivery of motors.  	Initially, based on *his ideas, he used the parallel motor* to drive the axle but could not stabilise the motor due to the axial torque produced by the gears and motor mount. He *played and explored* the other motor to observe its motion delivery. Later mentioned in the interview, " *perpendicular delivery is a much more stable configuration for the requirement of a rack and pinion gear system whereas one would use the parallel for the motor mounting the wheels.*"
Outcome: Through implementing his ideas, P1 experiences the instability of the motor as a challenge, and when he playfully explores in several iterations, he uses the motor that delivers motions perpendicular to the motor axis, which is seen to be a more stable configuration. Later he talks about the concept of motion delivery depending on the orientation of the motor /engine and the expected direction of motion.	
Participant 6	
Possibility of achieving an all-wheel drive electronically and not just mechanically.	This participant had a background in mechanical engineering and was seen using concepts of mechanical engineering primarily but had to use motors to power the bot. When the participant built the bot to climb the inclined, he used the differential for two wheels in front and two independently motor-powered wheels in the back. Later during a discussion, he mentioned, "*I realised I could use four motors when I started coding, but I had already built it, and I did not want to change it. Motors and coding is not the first thing that comes to my mind.* "

<table>
<tr><td colspan="2">Outcome: The participant, during the building process, is seen to work with the structure and mechanical solutions. He has not had exposure to programming, as he mentioned earlier. Through exploring and playing with the electronics and programming, he is seen to mention at times that he could have used motors, which indicates the change in his thought process considering electronics as alternates. During the interview, when he was asked if there had been any change in his thought process while answering, he mentioned, “ . . . . I realise now that many things could be achieved in EVs without the need for complex equipment like the differentials.”</td></tr>
<tr><td colspan="2">All Participants’</td></tr>
<tr><td>Affordances and the use of different components of Lego blocks, motors, sensors and the programming environment.</td><td rowspan="2">They solved the ordered challenges and problems that required them to progressively playfully explore the resources with scaffolds, allowing them to build the robots based on their understanding.

They performed actions on these bots to evaluate their idea of the build, and based on what they saw as feedback on their actions, they either modified or refined the ideas and the bots by making changes in the build or their approach to building the solution

Moreover, through the observed behaviour of the bots based on what participants coded they reflected on it. The reflections were sometimes triggered by some event or aided by mentor prompts. The participants then modify the code to modify the behaviour, eventually refining the code to exhibit the desired behaviour.

Eventually, all the participants can code the behaviours they desire and build the bot based on their ideas, exhibiting a gain of understanding of the affordances of the resources and the programming environment.</td></tr>
<tr><td>Controlling the behaviour of a robot by programming for receiving input and managing output accordingly.</td></tr>
<tr><td colspan="2">Outcome: All the participants are unaware of the Lego components’ affordances and the features of the EV 3 robotics controller (brick). The participants did not have exposure to controlling robot behaviours by inputs. Through playful exploration, using materials to build and work with their ideas in the physical space in an iterative manner while troubleshooting problems, they have been able to build robots by using various programming features and Lego components. They built a robot on their own that travelled a defined path and overcame an obstacle without any conceptually explicit instructions from a teacher or a mentor. They all mentioned developing confidence in electronic programming components to achieve desired behaviours. During the post-session interview, the participants were asked to talk verbally about building a pet feeding machine with Lego while they were not facing</td></tr>
</table>

the Lego components. As the participants talked about the solutions, they all specifically mentioned the pieces they would use and how. They also mentioned the sensors and motors they would use to mount them, explaining their behaviour with hand movements. They also discussed the code and the specific code blocks they would use to code their solutions.

The episodes presented above show that the participants can build and evaluate their understanding on the fly by following processes supported by Tinkery, leading them to perform actions on their physically built ideas. These ideas are their way of using materials, which can be interpreted as a representation of their conceptual understanding. Additionally, their ability to take multiple approaches to solve a problem and build different solutions allows them to develop varied perspectives, like in the case of P6, who realised that similar functions could be achieved by using electronic components and were able to implicate it to the design of electric vehicles. Similarly, P7 and P8 chose to seek assistance as they needed gears for their bots, and their bots were not behaving as per their understanding. The demo from the mentor allowed them to develop their understanding which they then implemented based on their respective ideas. Similarly, in the case of other participants, we see that certain processes, like using the material in their ways, when supported by certain features of Tinkery 2.0, provide participants with the opportunities to be able to test and develop their understanding of concepts.

Hence we could claim that the process of exploration, using materials in one's ways, considering multiple approaches to solving a problem and seeking relevant assistance has been shown to help the participants build a conceptual understanding. The mentor never had any instructional or informational interactions regarding the concepts. The demos were just a demonstration of using components like the gear demo demonstrated the use of two different types of gears on the wheel’s behaviour. Even here, the participants had to observe and reflect on observations to build an inference, and a gear demo was only given to participants seeking this information.

TC 3: Learners use materials in their ways and express ideas and emotions with artefacts and actions to display a sense of pride and agency in their solutions and problem-solving process.

&

TC 4: Learners take multiple approaches to solve problems, use materials in their ways and develop workarounds to develop confidence in their problem-solving process.

The evidence for these conjectures was analysed from the post-session interviews during which the participants were asked to discuss their experience working in Tinkery. They are also asked about any changes in how they usually approach problem-solving. Several episodes present the perceptions of students towards problem-solving in Tinkery 2.0. The episodes have been presented in detail in Appendix I under DBR2.

The important aspects of these episodes are the changes they report in the perceptions. As we observe in several instances, the participants talk about solving the problems using their ideas and working to build their solutions. This they report or claim with confidence and pride while being interviewed. As P1 mentions, *"Ya but that was not how I wanted to build the bot, I had thought to connect the motor directly to the bot so I wanted to go with my ideas. That is why I did not want to use the internet also, I wanted to think about my design and work on that".* Here he talks about wanting to use the motor directly and not using a transfer case; for him, being able to do it independently was an important aspect of his problems solving process. Not using the transfer case and the motor directly was his way of solving the problem. This impact we see here is his mentioning, "*I have not built anything before but, on the second day and today I have been able to build this bot. I am not able to believe this. I have just seen my friend who has built something and posted his picture and today I have been able to build it. I feel confident about using Lego and even making things"*. Here he talks about being able to build using Lego, which he is proud of and reported confidence in working with Lego and, in general, solving problems. Similarly, we can see in the detailed episodes P2 talks about being able to solve the third problem in his way using his ideas. Later he mentions that the problem could be solved in many ways as he started with a manual and later was able to build on his ideas and think of making further changes given the resources, which he said gave him confidence. This is also observed when he mentions an approach he would use to explore new kits. P3 mentioned using his ideas and displayed pride in doing so. Though he could not reflect on what had changed in his problem-solving process, when asked about specific problems, he talked about various ways of building them and said he was confident enough to find a way. For P4, like P3, being able to incorporate her ideas and the ability to solve problems on her own (agency) was her way of building confidence. P4, like P2, reported a sense of agency through solving problems in his way. For him, the confidence he developed is in realising that he should think in terms of the number of ways a problem could be solved and then choose the way he wants to try. This was similar for P7 and P8 as well. P6, like P1 but unlike others, shows a greater sense of pride in his thought and ways of solving the problem. Even he talks about the realisation of different ways of solving a problem, and this realisation helps him build confidence.

Something we see in common with all the participants is that they say they built the bots or solved the problems based on their own ideas, the way they wanted to do it. Through different processes, they could act and perceiver to realise their ideas by testing and moulding them as desired. They all, in their way, talk about using a feedback-based trial-and-error process to solve these problems. In the end, they claimed to be confident about solving these problems, especially by themselves and how they wanted to do it. Another point to note is that solving a problem in many ways is something all the participants were aware of, but when they say they realised to think of these multiple possibilities at the beginning. To convey this by saying things like take a pause and think of different solutions paths and then choose any based on some of their criteria. Also, when they feel stuck, they can always return to these ideas to figure out how to move ahead.

6.5 Discussion and Conclusions of DBR 2

This study aimed to evaluate if the design changes in Tinkery addressed the challenges and if the participants were tinkering. To do so, we sought to answer the following questions:-

6.5.1 Addressing Design Conjectures

To answer RQ 1 *What features and activities should a learning environment have to nurture tinkering?* We had a set of design conjectures we used to evaluate the role of various features of Tinkery 1.0. After DBR1, we had to make changes to some features, and we modified some of the old DCs and added two more DCs. The new set DCs help us analyse the new partial-manipulables, the function-based resource arrangement, the new challenge two and problem three, which are complex and have more solution possibilities and demos of the port view and the programming environment. These changes will help aid participants' process of playful exploration, building ideas as physical artefacts to seek feedback, using materials in their ways and expressing ideas and emotions with artefacts and actions. As presented in the episodes and then discussed in DC2` and DC3` the participants were seen playfully exploring with and using the new set of partial-manipulables given their variation in complexity and alignment to the problem domains as starting points or a reference in building their ideas' physically. Using them as a reference for ideas or understanding the use of various components also allowed the participants to express emotions like confidence and curiosity through actions like experimenting with the PM, taking the risk of trying something new based on the PM etc. Similarly, we saw that the new way of arranging the resources also aided the participants in their search and construction process by embedding the function of components as a feature of their placement in the environment. This, as told by the participants, led to easing in building their ideas as physical artefacts and performing actions as the search did not seem an overhead and also allowing them to use the materials in their ways by giving them a structure for searching components in a given space based on their functional requirement. This was supported by the observation and discussion presented for DC4`. The new open-ended problem three now has enough conceptual variables to play with, allowing the participants to take multiple approaches to design a solution which we see in the variation of the solutions designed as presented in the observation of DC8`. Similarly, new challenge 2 gave them exposure and confidence in using the programming environment. In addition to that, the demos of the programming environment were able to address the inhibition as we saw participants from all backgrounds programming using a variety of blocks as presented in the evidence of DC16. The demo of port view (serial monitor) allowed the participants to view the intermediate states of their solutions, as we see from the evidence of focused trials and reflection cycles as present in the observations of DC17. Hence we can claim that the changes in the scaffolds, i.e. the PM, the resource arrangement and the demos, now motivate and gradually get participants to try and use various resources. The capability of using a varied set of resources on the new open-ended problems, which allows several ways to achieve the solution's objective, got the participants to take multiple solutions and develop a wide variety of solutions. As more solutions were possible, the participants could think in their terms and solve problems as they wanted to eventually build confidence and show agency in the solution as they reported. Hence we can claim that these design changes have addressed the challenges of limited resource exploration and limited variability in solution possibilities.

In addition to the evidence on the design conjectures from DBR 1, with the evidence from the new design conjectures, we can claim that the design features of Tinkery 2.0 support the processes that aid tinkering in problem-solving. We saw that the participants were seen to explore playfully, have gotten formalised to focused trials and reflection cycles and continuously think and talk about evolving the solutions. We saw partial-manipulables, resource arrangement and demos supporting playful exploration, expression of ideas, iterative refinement, persistence & personal expression. The set of problems and their open-ended objectives support gradual exposure and complexity. Now we see a set of varied outcomes in terms of the solutions and the processes taken to solve the problems. This has allowed the participants to have been able to build solutions as per their ideas and understanding. Moreover, these features have also aided the extensive cycles of idea building and testing with additional components like gears, other pegs, and axles and opportunities to use them, leading to extensive variability in the solutions being developed.

6.5.2 Addressing Theoretical Conjectures

To answer RQ2, *How does the learning environment lead the learners to tinker?* We analysed the data for evidence for the theoretical conjectures. In the episodes for theoretical conjectures, we saw that playfully exploring resources, trying and testing their ideas as actions on their built artefacts, and iteratively troubleshooting challenges lead learners to persist and realise their solution ideas as physical objects (bots) which have been refined from where they started. Similarly, playfully exploring, using materials as they intended, trying multiple approaches to meet the solution objectives and seeking relevant feedback allowed the participants to develop their concepts about using Lego and the domain of sensors, mechanical components and programming, as we saw in the evidence of TC2. In addition, participants have been observed using material as desired participants, being able to express their solution ideas as evolved physical bots that they have built. They have also been observed to show emotions like confidence and curiosity through actions like focused trial and reflection cycles, taking the risk of trying new ideas based on inspirations or insights into operational or conceptual knowledge gained. Through these processes, the participants have reported a sense of pride and ownership (agency) in their problem-solving process and also reported having developed confidence in using resources and the concepts of the domain of vehicular robotics, as seen in the observation of TC 3 and TC4. Sure, participants who discuss experiencing this new way of focused trial and reflection cycles have reported confidence in using such a problem-solving process. Participants displaying persistence in solving problems in their way, building changes in conceptual understanding of the resources as well as the domain and showing a sense of confidence, pride and agency in their problem-solving process and the solution is markers of a tinkerer as reported by literature (Petrich et al., 2017).

Now when we look at both the theoretical and design conjectures together for participants who worked in Tinkery 2.0, the design conjectures show how the features of the learning environment, like the scaffolds, the problems and the mentor, aid the processes like playful exploration, building one idea as physical resources, using the material in their ways, iterative troubleshooting, taking multiple approaches to solve a problem and building their ideas as artefacts and displaying their emotions with actions. As participants follow these processes, the theoretical conjecture shows that they persist, develop conceptual understanding and show confidence, pride, and agency in their problem-solving process and meeting the solution objectives. Hence, the features of Tinkery 2.0 aid the processing that gets the participants to display behaviours identified with tinkering, so Tinkery 2.0 does make the participants tinker.

Chapter 7

Discussion

We begin this chapter with an overview of the research work through this thesis and then provide a summary of the findings. We discuss the various aspects of tinkering that have been seen to play a role in problem-solving and how our findings relate to those in the existing literature. We close this chapter by discussing limitations and the generalisability of the results of this research work.

7.1 Overview of the Research

The need for this research arose from the gaps in current practices associated with tinkering with problem-solving, as discussed in Chapter 2. We address this by focusing on *designing to nurture tinkering as a means for problem-solving in engineering design.* To do so, we first looked at various definitions of tinkering in section 2.1 and summarised them from the perspectives related to the nature of activities, the goals, visible processes and orientation. In the definition, we included the perspective of tinkering as evolving a solution by building experiences of exploration and play. In sections 2.2 and 2.3, we reviewed best practices of tinkering in terms of environment, tasks, other actors and orientation towards activities. In section 2.4, we argued for tinkering as a plausible and suitable approach to solving ill-structured engineering design problems. To enable nurturing of tinkering, we choose to design a learning environment. We first analysed expert data regarding their perspectives on tinkering and their suggestions to promote tinkering. Section 4.1 discussed how we coded these perspectives into physical aspects of thinking, like characteristics of materials and the space with its arrangement, and personality traits like encouraging dialogue with materials, prompting action in physical space, ensuring agency, scaffolding attitude towards problems, mistakes & challenges and providing opportunities and scaffolds for transitions between states. We also explored the role of a mentor in supporting tinkering. Tinkering is favoured when there is seamless interaction with the availability of information and reflective triggers through a mentor as questions and prompts, as discussed in section 4.2.

Hence as suggested by researchers in literature and our explorations, learning environments to nurture tinkering should scaffold exploration, encourage play, contextualise problems, progressively formalise learners and support an evolutionary mindset. This led to the design of our first learning environment, Tinkery 1.0, for problem-solving in Lego robotics, as discussed in section 4.3. It also informed the pedagogy, choice of resources, design of problems, scaffolds and the roles of a mentor. We used conjecture mapping to determine how the elements of Tinkery 1.0 aided the tinkering processes and evaluated them with a study discussed through sections 5.1 to 5.3. This study found evidence for most design conjectures and uncovered challenges regarding a few other conjectures discussed in section 5.4. We again referred to literature to address the challenges and made changes in the design, which led to the second version, Tinkery 2.0, discussed in 6.1 and 6.2. In the study with Tinkery 2.0, the redesign was evaluated for the support provided by Tinkery 2.0 features to the learners' tinkering processes. We found evidence for the tinkering processes leading to the outcomes in the domains of effect, cognition and effect, as discussed in section 6.4. Learners who solved problems in Tinkery 2.0 used several processes of tinkering to solve the problems. The findings are summarised in the following section.

Table 7.1: Summary of Findings and Conclusions.

Se No.	Findings	Conclusion
1	Partial manipulables kindled curiosity among participants to engage in playful exploration of materials and ideas, and spatial arrangement with demos supported them. Physical characteristics used for the arrangement of resources,like functional affordance and structural affordance when aligned to the need of the problem, support exploration and experimentation with resources.	Partial Manuplables in the building environment trigger exploration and quick experimentation, aiding the tinkering processes. Resources, when laid out based on characteristics that align with the need of the problem (form/function), aid the exploration of various resources and quick experimentation based on their characteristics which supports the processes of tinkering.
2	The ordered set of open-ended problems in a physical space with multiple possible solutions allowed the participants to start with simple solutions, gradually	An ordered set of problems allows the learners to progressive formalise with the resources giving them enough opportunity to tinker with them.

	increasing their complexity to allow a wide variety of solutions.	Problems with a low floor, high ceiling and wide walls provide them with the agency to start simple, increase complexity and try variations as they desire, aiding their attitude as a tinkerer.
3	Specifying the role of mentors ensures that they scaffold the participants into tinkering without influencing their problem-solving process or the solutions.	Mentors' roles act as a guide to scaffold reflections on learners' actions while providing just-in-time feedback allowing learners to take a tinkering attitude while keeping a check on inducing bias in their ideas.
4	Students were observed persisting through challenges to get to their goals. They demonstrated a gain in conceptual understanding. They displayed a sense of pride and agency and reported a gain in confidence when solving engineering design problems.	When solving problems in tinkery, learners show gain in cognitive, behavioural and affective domains, which align with the learning dimensions framework for tinkering and making-based activities. This implies the learners were tinkering while solving problems.
5	Participants performed actions of physical artefacts for which they observed certain behaviours, which revealed new possibilities or simpler ways to solve their challenges which they had not thought of or were complex to comprehend mentally.	The short cycles of exploration and experimental play when tinkering with physical artefacts allows the possibilities of a sequence of epistemic and pragmatic actions, which ease the cognitive load in the problem-solving process.
6	Participants were observed arranging resources around their solution, which they later mentioned were to help them keep track of ideas they wanted to experiment with.	Though tinkering might seem like a set of random actions, learners figure out processes of tracking and tracing options by using the physical environment offloading the mental load.
7	Experienced participants who were fixated on a solution idea were seen persevering by tinkering and eventually evolving the initial ideas.	Tinkering allows learners to set self-goals, experience their ideas and persevere to realise them through continuous feedback, allowing learners to overcome design fixation.

7.2 Discussion of research findings

Tinkery 1.0 and 2.0 features were designed to support several processes that mediate learners' problem-solving. We conducted two studies; the first study with Tinkery 1.0 focused on design conjectures DC1 to DC15 to observe the interactions of the participants and their behaviour towards solving the problems. Analysis from Study 1 provided supporting evidence for the use of partial-manipulables, an ordered set of open-ended problems and the various roles of the mentors in getting the participant to playfully explore, perform actions artefacts that they build, consider multiple opportunities, use materials in their ways, troubleshoot iteratively, develop workarounds and seek meaningful assistance covering most of the design conjectures. It also uncovered gaps in the resource arrangement, the complexity and variability of partial manipulables, and the variability in possible solutions to the problem. Based on the analysis of the challenges and recommendations from existing research, we redesigned the problems, including more variability in the complexity of the partial manipulables and the arrangement of resources in terms of functional affordances. We also included demos for the programming environment and port view features. We revised the relevant design conjectures to analyse the redesign and tested DC2`, DC3`, DC4` and DC8`. The episodes observed for the new design conjectures show that the new problems were sufficiently complex to get students to tinker and allowed solutions to vary. The redesign encouraged participants to use complex components in the partial-manipulables and to explore more components based on their requirements playfully. This led them to perform the experimental play and build diverse solutions. Demos encouraged the participants to use features like port view and motor controller to test intermediate states and remove inhibition towards exploring the programming environment using it extensively.

In addition to the design conjectures, we analysed the tinkering processes that mediate problem-solving and their influence on behavioural, cognitive and affective outcomes. These were evaluated via the theoretical conjectures (TC) 1-4. Playfully exploring resources, trying and testing their ideas as actions on their built artefacts, and iteratively troubleshooting challenges led learners to persist and realise their solution ideas as physical objects (bots) refined from where they started. Similarly playful,ly exploring, using materials as they intended, trying multiple approaches to meet the solution objectives and seeking relevant feedback allowed the participants to develop their concepts about not just using Lego but also the domain of sensors, mechanical components and programming. Participants used material as desired to express their solution ideas as evolved physical objects they built. They showed confidence and curiosity through focused trial and reflection cycles, taking the risk of trying new ideas and reporting a sense of pride and ownership in their problem-solving process. Overall, the findings show that learners developed high persistence to meet solution requirements, gain conceptual knowledge and develop confidence and agency.

Features like partial manipulables kindled curiosity among participants to engage in playful exploration of materials and ideas, and features as the spatial arrangement with demos supported them. Prior research has discussed the arrangement of resources based on their physical characteristics (Brahms & Werner, 2013), and we extended it by suggesting the physical characteristics of the resources, like functional affordance and structural affordance, should be aligned with the need for the problem. E.g. We use functional affordances as a characteristic for the arrangement of problems that require the solution to achieve a function. If the problem requires the solution to be structural, then we recommend the arrangement to be structural. This further aligns with the theory of distributed cognition, where the functional arrangement acts as a memory of the function of the resources (Hutchins, 2000), thus easing learners' search based on the functional requirement.

Similarly, researchers and practitioners have talked about keeping completed or incomplete models around as inspiration (Honey & Kanter, 2013; Resnick & Robinson, 2017). We designed partial-manipulables that did not just act as inspiration but also as an aid to the problem-solving process as a quick way to try and test one's ideas, extending these recommendations. We found that demos and not merely usage instructions of important operational features like the "port view" reduced the inhibition of the participants and gave them the confidence to use the tools. This conforms to the recommendations made by the researchers on the demonstration of important tools in context (Resnick & Rosenbaum, 2013).

The ordered set of open-ended problems situated in a physical space with multiple possible solutions gave the participants a low floor to start with simple solutions, as seen during the process of solving problem 1, high ceiling to allow very complex solutions, as seen with the solutions of problem two and wide walls to allow a wide variety of solutions. These findings conform to the recommendations on progressive sets of open-ended problems (Honey & Kanter, 2013). Through the incorporation of recommendations on problem-solving literature on the use of multiple conceptual variables and change in context for difficult problems (Viswanathan & Linsey, 2013), we ensured change in the context of the complex problem two from problem one and incorporating a number of conceptual variables leading to a wide variety of solutions based on the variable the participant chooses to work with. We also observed that situating the problems as a part of the characteristics of the physical space allowed the participants to play with their ideas as physical artefacts in the space to evaluate expected behaviours and make modifications on the go, aiding the quick cycles of playful exploration and experimental play to evolve their ideas into solutions. This observation not only confirms the recommendation on situating the exploration and play within the subject matter (Petrich et al., 2017) but extends it as it also incorporates the theories of anchored instruction (Bransford et al., 1990) by using the physical space to build a narrative that presents a realistic (but fictional) situation.

Moreover, building and working in this physical space allows extensive and diverse opportunities for participants to explore the problem and discover subgoals for solving the problem. For learning with tinkering, the literature claims that instead of problems, one must give themes and allow the learners to incorporate their interests (Resnick & Robinson, 2017). This has its importance for learning, but for problem-solving in real-life situations, one is bound by constraints like time and resources; hence for tinkering in problem-solving, we choose problems which are closer to the real scenarios. The problems still follow a low floor, high ceilings and wide walls, allowing the learners to take the desired approach.

We also found that specifying the role of mentors ensures that they scaffold the participants into tinkering without influencing their problem-solving process or the solutions. Mentors in these roles focus on maintaining a balance between intervening and not intervening, playing the role of a safety net and ensuring that they question why something that happened did happen. These roles are an extension of the best practice recommendations for instructors (Honey & Kanter, 2013; Martinez & Stager, 2013; Resnick & Robinson, 2017).

7.3 How tinkering mediates problem-solving

In this section, we look at the role of various aspects of tinkering in learners' problem-solving that have been derived based on the observations we made during the studies. We discuss the role of physicality and situatedness of the activity, the role of prior experience, the role of the resources and the way they are arranged and finally, the role of mentors and manuals.

Role of physicality and situatedness: One aspect of Tinkery 2.0 was the situatedness of the problem and solution requirements in the physical space. Based on observing how the participants use the space and the various components, we suggest the role of distributed cognition in helping them get ideas. In addition, situatedness acts as a memory of possible ways learners take while solving problems (Martin & Schwartz, 2005). Learners are seen arranging pieces near and around their building spaces which they stated were ideas or options they were to try. Similarly, some learners mentioned looking at the trays helped them see pieces that gave them ideas, or at certain stages, they referred to certain pieces or components they had seen in a specific tray that could help them make the connection or build a frame. Hence such instances suggest the role of physical space and resources in the process of solving problems. Even partial-manipulables have been seen to play a role in memory of ideas and ways of using components.

The other role of physicality and situatedness in Tinkery 2.0 was how the participants did it during the trial and reflection cycles. In a number of instances, the participants were seen trying multiple options that could help them solve the problem in different ways. For example, to make a multi-beam/frame connection, they tried all different pegs and based on the outcome, they used the desired peg in different places to achieve the build. Here the actions of trying each and every peg allowed them to decide on the process they would use to connect the frames and the beams. These are suggestive of epistemic and pragmatic actions. The epistemic actions, like trying all the types of pegs, allowed the participants to narrow down to one peg, suggesting the epistemic nature of the trial (Kirsh & Maglio, 1994). Now with one peg connecting different components in different ways to achieve the build allowed them to reach their goal is suggestive of such actions being pragmatic (Kirsh & Maglio, 1994). Similar instances of a combination of epistemic and pragmatic actions were observed with a number of participants at various stages. These vary in levels, like on a broader scale, applying or building one idea out of many available options as a base to work their ideas out.

Another example is trying degrees and/or rotations to code the bot by rotating the wheels with hands and observing the changes in the port view (epistemic actions) and then using one or a combination to program the path by manually dragging the bot on the floor to derive an estimate of the number of rotations required to travel a specified distance or to turn. Then we saw participants arranging components or placing components on their bots at intermediate states to get a sense of how multiple variations in components and arrangement would look or behave (epistemic actions), then following either of the combinations to achieve the desired solution with solution built (pragmatic action). Another case was of participants trying various sensors to see which can be used to make measurements and, in this process, measuring various objects in the room with multiple sensors (epistemic actions) and later using those objects (like floor tiles) to calculate the dimension of the room (pragmatic actions). In this case, the interesting observation is that everyone took a similar set of epistemic actions, but their own decisions of using various objects as reference led to different pragmatic actions. Hence the physicality and situatedness of the problems and solution objectives do seem to have aided the participants by allowing them to use the physical space as a memory (distributed cognition) and take actions that helped them get and decide among various solution paths (epistemic actions) followed by actions that helped them get to the objectives of the solutions (pragmatic actions).

Role of Prior Experience: Participants who had some prior experience in the domain of robotics were seen to be biassed with ideas from these previous experiences. They tend to try and fit those ideas into the solution. This is commonly known as design fixation in literature (Jansson & Smith, 1991), which is a known problem with many novice and experienced designers (Linsey et al., 2010). Interestingly with tinkering, though, these participants started with their old ideas; fixation led to perseverance and eventually, the ideas they were fixated on evolved to solve the problems. Fixation in tinkering could lead to refined solutions, but only in the case of people who are very highly motivated and confident towards their solutions. To design for tinkering, we must consider that an individual's prior experiences are very specialised and specific; hence the problems require a mix of conceptual expertise, forcing them to break fixation from prior experience, which can be eased with scaffolding and mentor intervention. Whereas the new participants were seen feeling daunted at times, the ordered set of problems eased them into the building process. Additionally, the inclusion of manuals and allowing partial-manipulables help them choose a starting point from where they are constantly searching for different designs and inspirations. Hence such design decisions help make tinkering-based activities inclusive for people with different experiences.

Role of manuals and mentors: The observations from the studies contain certain implications for the role of the mentor and the use of a manual. The impact of allowing participants to use the

instruction manual allowed some participants to overcome inhibition in trying things out as they were all new to the Lego robotics sets. The approaches were seen to be similar till problem two based on inspirations from manuals but then became personalised and varied for each of them for problem 3. The initial two challenges were solved without the use of the manual. Challenge 2 and problem one were designed in a way such that the manual-based solutions provided participants with a start to overcoming the fear of using Lego components. As they progressed, they got to know about the affordance of components. Problem 2, when solved with the help of the manual, also helped these certain participants with direction and enough confidence for problem 3. None of the manual models was relevant to problem three; hence the participants had to figure out the solution on their own for problem three. However, the direction from problem two solutions from the manual allowed them to think, build and experiment with their ideas. Hence manuals can play an essential role when used as inspiration or as part of the progressive problem-solving process.
The choice of using or not using the manual should rather remain with the participant. If manuals are to be used independently, they should follow with open-ended project problems without the need to give solutions and let learners figure out the solutions themselves. Scaffolds can be in terms of resource arrangements and small bots like PMs that align with certain aspects of the solutions, which could be based on the building part of the manual. The mentor also is important for a learning environment that nurtures tinkering. We use the term mentor because they play the role of a non-contributing participant. This means they are as involved as the participant in problem-solving yet do not directly contribute to the solution process, leaving the agency of solving the problem with the learner. They act as a safety net under which learners can work as they please. They let the learners fail, aid them to reflect and get back but ensure that the learners do end up hurting themselves. The mentor has to be as involved in their solving process, scaffolding them towards a habit of checking and reflecting on their problem-solving process and eventually tinkering independently.

The Role of Resources and Tools: One other important observation we made was participants tend to arrange resources as per their requirements which not just eases the search process but acts as their offloaded memory in the physical space easing their cognitive load (Sweller, 1988). They then use this arrangement to try a number of variations with different components that are similar in structure/function. Hence the arrangement is not just mere categorisation of resources but can also aid the thought processes during problem-solving. When made in tinkering-based activities, such design decisions can make or break the problem-solving process and must be thought out well. In addition to the resources, there are some tools, like serial monitors and controllers, which help quickly simulate or test the intermediate states of the solutions. In the case of Lego Mindstorms, it was the port view and motor controller. Tools like serial monitors play an important role, and this is how one makes the black box into a glass box by allowing observation of the system's functioning. Hence one must ensure learners are exposed to the functioning and usage not just by instruction but by demoing them in the context of the problem.

7.4 Claims

Tinkery 1.0 and 2.0 design features, along with the Xpresev pedagogy, nurture tinkering when solving engineering design problems.

The analysis from both studies suggests that intended outcomes for tinkering were mediated by the processes observed as participants solved robotics design problems using Tinkery 1.0 and 2.0 in the two studies, respectively. Participants were seen 1) to engage in playful exploration of materials and ideas, 2) perform actions on built artefacts and use the feedback they received from the artefacts through physical observation, 3) iteratively perform these action-feedback-action cycles to troubleshoot challenges or develop workaround and 4) They were seen to persist in their own way to meet the solution requirement which is known hallmarks of tinkering (Petrich et al., 2017). These were observed as they worked with features of Tinkery 1.0 and 2.0 like resource arrangement, scaffolds like partial-manipulable and demos, open-ended broad solutions requirements, non-directive, supportive behaviour of the mentor, and freedom to solve problems in their ways. The Xpresev's pedagogy supported progressive formalisation into exploration, experimental play (solving) and evolving a solution. Hence we claim that the features of Tinkery 1.0 and 2.0, along with the Xperseve pedagogy, nurture tinkering when solving engineering design problems of educational robotics using Lego Mindstorms.

Supporting a sense of agency of the learner in the problem-solving process is essential to nurture tinkering for problem-solving. The role of each element of the learning environment should be designed to support the learner in what they want to do.

Based on our observation of learners' tinkering and analysis of such episodes, we see that tinkering by nature is a doer (learner) centric activity. Hence if a problem-solving activity is designed to allow tinkering, the design must ensure agency with the learners. The agency has been seen to provide a sense of ownership which was found to be motivating and builds the learners' confidence, as they reported. It was observed tinkering allows learners to choose their problem-solving path and change things on the go and as they feel like it. Learners overcome their inhibitions in robotics, show confidence in using Lego, and discuss various ideas and projects they now think they can do. The role of every element of the environment should be to support the learner in what they want to do.

Building ideas physically as artefacts and performing actions on those artefacts while situated in the problem space eases the problem-solving process for learners.

a. **Physicality allowed learners to take actions that were epistemic and/or pragmatic.**
b. **They also used the properties of the physical environment, like arrangement and classification, as a memory of resources and ideas.**

Learners reported "enjoying this iterative style of building, observing, testing to solve problems and stated they want to use it more often". When asked to solve problems hypothetically, some learners' process shows focused trial and error cycles. These iterations were the key moments where learners got stuck, overcame and had their 'Aha' moments which were closely associated with the actions they did on their own or were triggered through mentor prompts. Through close observations, their actions were initially seen as epistemic, leading them towards some pragmatic actions to achieve objectives. These actions seem to ease the cognitive load of problem-solving. Being physically present in the problem environment allowed such actions to be performed. Moreover, using the features of the environment, like the arrangement and placement of resources or half-built artefacts, further seems to reduce the cognitive load by acting as an offloaded physical memory of their ideas distributed around them as they solve the problem.

A mentor can aid the nurturing of tinkering for problem-solving as a non-contributing participant by providing reflection prompts, triggers for actions and checks, assurances and allowing the learners to learn from failure.

Though tinkering has been considered a loner's activity, we have observed that nurturing tinkering can be supported by a mentor. However, the role of the mentor should also be of a non-contributing participant who is as engaged as the learners. Let the learner drive the activity through various roles discussed before.

7.5 Limitations

In this section, we discuss the limitations of our research work in terms of the learning environment, the research design and the learner's attributes.

7.5.1 Limitations Related to Learning Environment

In this research, we chose to go with an off-the-shelf tinkerable robotics kit, the Lego Mindstorms EV3; hence the evaluations are limited to using Lego Mindstorms as the construction resource with the use of tools that come along with it. As mentioned earlier, the reason for this choice was the familiarity of the kit with the researchers as a specific set of building resources that ease the observation and analysis of the interactions of the participants and the resources. Additionally, Lego is built based on the recommendations of tinkerability (Resnick & Rosenbaum, 2013). A number of other sets of resources could also be used as long as they have been designed or evaluated for tinkerability.

The current observations have been made based on a set of problems designed for vehicular robotics to be solved with Lego Mindstorms EV3. This theme was broad enough for a varied set of problems to be framed, like travelling from A to B, autonomous driving and obstacle avoidance. The participants solved problems based on these aspects, and their solving processes were evaluated for these specific problems of vehicular robotics.

This research was based on the interaction of an independent learner when solving problems in a tinkerable environment; hence collaboration was out of scope. Moreover, understanding tinkering in a personal setting is complex, and with collaboration, the number of influencing factors increases. Additionally, through the exploration of literature classically (Louridas, 1999), tinkering (bricolage) has been known as a loners activity, whereas most of the current literature focuses on learning with tinkering in collaborative environments; hence we choose to explore tinkering in an individual setting and as a future perspective suggest exploration and comparison of collaborations in such learning environments.

7.5.2 Limitations Related to Research Design

This research aimed to design learning that nurtures tinkering; hence that was the only evaluation criterion for all our research studies. We chose not to measure the impact on problem-solving parameters like efficiency or creativity as the idea was to focus on tinkering as long as the solution was able to perform the tasks required by the problems. We did not intend to compare tinkering with other problems solving processes hence did not evaluate the time taken to solve or the quality or efficiency of the solutions designed by the participants. However, such comparisons have been made in the literature (Quan & Gupta, 2019), which have suggested a more nuanced understanding of productivity (of tinkering and other design practices), which is local and defined with respect to specific goals and actors.

During our study, the researcher himself was the mentor as well, who followed the procedures mentioned in the guidelines. Since no other person other than the mentor was trained to ensure consistency among studies, the guidelines for the purpose of mentor training were never evaluated. This is also a prospect for researchers who want to explore the mentor guidelines further.

Results discussed in this thesis from the two studies are from a lab setting where an individual was tinkering with a given kit, solving the given set of problems under specific conditions. The implications of these results may vary in other environments like engineering labs, classrooms, and hackathons; hence similar implementations in such an environment may require a redesign based on the guidelines. Additionally, the sample size of the participants could be bigger due to the limited availability of participants who agreed to come to the lab for three days physically. In addition, the restrictions due to COVID-19 also limited the number of studies and participants we could invite. Yet we have a substantial number of instances of interactions and episodes of observations to support our claims apart from a limit to the generalizability of the LE to students from UG and PG engineering courses specialising in computers, electronics and mechanical engineering, which has been discussed in the next section. Our participants were seen to be motivated to work with Lego, so motivation could have driven the reason for choosing to participate. We also do not claim that students who work with Tinkery 2.0 become tinkerers. Still, when they work with Tinkery 2.0, they tinker as they all reported liking this way of trying this out and solving iteratively through cycles of exploration and play.

7.6 Generalisability

This thesis aimed to design a learning environment for nurturing tinkering for problem-solving in engineering design and analyse if the learners tinker to solve the given engineering design problems. The Xpresev pedagogy with the learning environment Tinkery 2.0 is the central part of the research. We, therefore, examine the claims of the thesis for generalizability of the learning environment design and other problems and objectives.

7.6.1 Design of the Learning Environment.

Tinkery 2.0 has been designed based on best practices from the literature and the recommendations from experts' analysis. It has evolved through analysing learners' interactions and their features in two cycles of DBR. Tinkery 2.0 was designed for an ordered set of open problems with multiple possible solutions. The analysis was done with participants from UG and PG engineering courses in computers, electronics and mechanical. Hence Tinkery 2.0 will be appropriate for any learner from a similar cohort with the same set of problems. If one chooses to include different problems, one may partially modify the existing problems, such as adding a different set of obstacles or challenges. One may also change the entire set of problems from engineering design as long as they abide by the guidelines mentioned in section 8.1.4 and update the scaffolds accordingly. One may even change the resources as long as they align with the requirements of tinkerability (Resnick & Rosenbaum, 2013). The partial-manupliables and the arrangement of these resources will also have to be modified per the guidelines. As per the guidelines, the mentors will have to work with the resources and have solved the problems themselves. One may change the duration of the intervention in the LE as long as enough time has been spent on the three aspects of the pedagogy, namely explore, solve and evolve. Based on our exploration in the current form of Tinkery 2.0, a minimum of 3 hours is needed to be spent on each aspect and divided the sessions into three days. This eases the participants' thought processes and helps them reflect post their sessions, as each session is intense. One may even choose longer sessions but with breaks every three hours. The duration will also depend on the tasks/activities and the time required in a building with the resources; hence, one must consider this while trying to solve the problem.

7.6.2 Problem-Solving in Other Domains.

The design of Tinkery 2.0 was primarily for problem-solving in engineering design, and we chose the problems from vehicular robotics based on a survey of problems usually given with Lego kits, general workshop problems and our exploration and expertise with the equipment. One may use Tinkery 2.0 for a different engineering domain where physical resources are important. This would require changing the problems, the resources, and demos or might need some more domain-specific scaffolds. The pedagogy will ensure the learners are gradually exposed to exploration, play and reflections to evolve their solutions. Problem sets can also be from various engineering design domains while ensuring they require a physical artefact to be built as a solution. They can be solved with the given resources and have corresponding scaffolds designed per the guidelines. Domains like computer networks might not have physical resources but could use simulators that are close to the production environments and can have scenarios based implementations that have real-life implications. Such situated scenarios could work, but this will require additional research, which has been discussed in future work. In that case, one would need to design an entirely new learning environment using the pedagogy and the guidelines and evaluate the simulator for tinkerability. Such a LE should be able to nurture tinkering and would need a few cycles of DBR to evolve the design features.

Problem-solving, apart from engineering design, could benefit from tinkering as a problem-solving strategy. The LE design guidelines or Tinkery 2.0 could serve as a starting point. The research methods from this thesis could act as candidates for carrying out similar research in other domains of medicine, maths, and arts for which there have been attempts, as reported in the literature (Knowles, 1987; Lewis & Thurman, 2019; Mol et al., 2015). Similarly, there has been a research interest in tinkering for skill-based training like creativity and methods of inquiry (Ragnoli et al., 2022; Wargo, 2018), which could also use the guidelines, Tinkery 2.0 and the research methods from this thesis as the basis of research for designing a LE for such domains.

7.6.3 Objectives of Tinkering and Problem-Solving

The objective of Tinkery 2.0 was nurturing tinkering for problem-solving. We found that students indeed solved problems effectively by using a tinkering approach. In addition, we found emergent conceptual learning. Hence learning environments like Tinkery 2.0 can be used for problem-solving and conceptual learning with the addition of a few reflection prompts at the end.

One may even use such LEs for skills like troubleshooting, design etc. Such LEs can be used along with problem-based or project-based environments.

Chapter 8

Conclusion

This chapter discusses the contribution of this thesis, further experimentations and investigations based on the research directions of the thesis, and the final reflections of the researcher.

8.1 Contributions

This research contributes to the existing knowledge of the design and development of learning environments, specifically in terms of scaffolding, pedagogy and the role of a mentor in aiding practices like tinkering in engineering design problem-solving. Additionally, it emphasises the role of learners' agency and presents guidelines on how it can be nurtured to promote tinkering. The contributions are in the learning environment Tinkery, the pedagogy Xpresev, various roles a mentor needs to assume and the guidelines for designing for such a tinkering environment. Regarding tinkering as an individual activity, there has been a lack of recommendations regarding the pedagogy and the role of the mentor; hence this research fills that gap. The contributions and their implications for various groups have been discussed further.

8.1.1 Tinkery 2.0 - the learning environment

Tinkery 2.0, in its current version, gets learners to tinker to solve engineering design problems in vehicular robotics while using a Lego Mindstorm EV3 kit. Tinkery 2.0 in its current version gets learners to tinker to solve engineering design problems in the domain of vehicular robotics while using a Lego Mindstorm EV3 kit, which Tinkery 2.0 in its current version gets learners to tinker to solve engineering design problems in the domain of vehicular robotics while using a Lego Mindstorm EV3 kit. Tinkery consists of open-ended problems, partial-manipulable, function-based arrangement of resources, demos of the programming environment, and serial monitors. It also specifies the role of a mentor. A related contribution is a plan for a 3-day workshop for learners to interact with Tinkery and solve engineering design problems productively. Day 1 includes activities that get learners to explore and play with the resources by solving focused challenges. Day 2 requires learners to solve a problem to achieve basic functionality, allowing them to implement their ideas while also allowing a manual-based solution to start with. Day 3 asks learners to solve conceptually complex problems without a manual-based solution. Learners evolve their processes and solutions from Days 1 & 2, wherein they think, build, act and refine their ideas to get to a bot that could achieve the solution objective set by the problem.

Who can benefit: Tinkery in its current form can be used by anyone with a Lego Mindstorms kit who wants to expose learners to tinkering to get them to build robots that can move and climb. Additionally, with relevant conceptual reflection prompts, this can also be used to build a basic conceptual understanding of vehicular robotics. With modification per guidelines, one may even use it for a different robotics domain with a new set of problems. Additionally, modifying the partial-manipulable resource arrangement as per a new engineering design kit and the basis of the problem can also be used with a different kit other than Lego Mindstorms. This can also be used by researchers who wish to examine other aspects of tinkering like efficiency, collaboration etc.

8.1.2 Xpresev pedagogy

The pedagogy independently supports any tinkering-based learning activities or a learning environment. The pedagogy primarily comprises three phases: -

- **Explore**: Emphasises free exploration to capture intrinsic motivation. Learners start with small problems, which require them to interact with the physical space using the components available in the surroundings to solve the given problem.

- **Solve**: Focuses on externalising a learner's idea regarding the resources available in the surrounding. This can be done by allowing the learners to start building solutions for minor component problems by using the affordances of materials explored in the previous phase and using them to externalise their ideas.

- **Evolve**: Learners are encouraged to identify personalised objectives for solutions. Then to meet those objectives, they are triggered to discover emergent challenges and overcome them through iterations of a focused exploration and play with the available resources and ideas. Here they evolve their solution process and the solutions while maintaining agency in them.

Additionally, a 3-day workshop plan for learners to productively interact with Tinkery and solve engineering design problems. Day 1 includes activities that get learners to explore and play with the resources by solving focused challenges. Day 2 requires learners to solve a problem to achieve basic functionality, allowing them to implement their own ideas and use a manual-based solution to start with. Day 3 asks learners to solve conceptually complex problems without a manual-based solution. Learners evolve their processes and solutions from Days 1 & 2, wherein they think, build, act and refine their ideas to get to a bot that could achieve the solution objective set by the problem.

Who can benefit: This pedagogy can be used as the basis for any learning activities or learning environments as it gradually formalises learners to the processes or practices of any problem-solving approach. In its current form, the activities are designed to support tinkering. It can be directly used for allowing tinkering as a method of solving problems or conceptual learning. Additionally, it can be used by researchers who aim to use or evaluate tinkering-based learning methods or learning environments.

8.1.3: Mentor Roles

The mentor in Tinkery 1.0 and 2.0 is a non-contributing companion who plays several crucial roles in supporting the learners while allowing them agency in the solution process and opportunities to evolve it. Mentors assist the learner with the following: -

- **Reflection prompts:** The reflections can be via asking questions requiring the learners to reason or through analogies to get the learner thinking.

- **Direct Prompts:** To get learners to focus attention or break inhibition by taking actions on what they are building or getting them to build and try with what the learners are thinking.

- **Just-in-time information:** Providing operational information or demonstrations to aid the problem-solving process of the learners.

- **Reassurances:** To address learners' inhibition when choosing from some options and leading them to take action. Also, to address frustration when stuck at some problem, get them to accept the limitation regarding ideas or conceptual understanding, and get them to think of alternatives.

- **Abstain from intervening:** To let learners pursue their solution process and experience the outcomes. Even if the outcomes might sometimes be failures, it is an essential experience to get the participants to accept them and think of them as alternate realities.

Who can benefit: Based on an initial exploration with different chatbots and personal robots, we believe this classification of mentor actions in their various roles can be used for building a semi-automated tinkering companion who can even be extended to help the mentors mediate sessions using a set of such companions tied to mentor facing platform or a dashboard. These classification and mentor guidelines can also be used for mentor training for workshop settings which would like to exploit the advantages of tinkering. This also has implications for researchers, instruction designers, ed tech companies, and colleges aiming to design tinkering-based learning environments, activities, tinkering kits, or training modules from the point of view of mentor training and automation of a mentor or learning companion.

8.1.4: Design Guidelines for a Tinkering-based learning environment.

Based on the observations made during the design and evaluation of Tinkery 2.0, we evolved guidelines for designing a learning environment for nurturing tinkering as one solves learning design problems. We took a flexible and general approach in writing these guidelines so they can be applied to various contexts and problems. They are not limited to engineering design in robotics but are written to encompass broader principles and concepts applicable across disciplines.

Problems: Hierarchy in problem design allows framing initial problems as possible subproblems for the further complex problems ahead. In the initial problems, one can make the learners practise basic principles and procedures.

- The problems should gradually increase in complexity. The initial problems should focus on a specific affordance of a resource required to solve a specific problem. Subsequent problems should be more complex, based on the number of resources and the possible combination of their affordances. Another approach is to include several conceptual variables required to solve the problem. As the problems increase in complexity, one must also ensure there are several possible solutions. This can also be achieved by keeping the solution objectives broad, requiring managing several influencing variables or concepts that must work together to solve the problem. Here the learners will have the opportunity to do playful exploration to decide which resources and how they would want to use them.
- The problem design and the resource availability must ensure several possible ways of reaching the solution. This can be ensured by providing resources that provide multiple starting points for the solution and allowing learners to start with any resources and explore and play with them. Even if the solutions are similar, having multiple solutions paths will enable learners to build agency towards their problem-solving process.
- Another important aspect is ensuring the problems are situated in a very relatable and physical context which can be achieved by grounding the problems as activities as a part of a scenario in a physical space. Problems require working with characteristics of the physical spaces, like objects in the space, floor area, walls etc., OR designing solution objectives that require using characteristics of a created physical environment.

Pedagogy: The essential aspects of tinkering to solve problems are exploring what we have and what we want to do, solving with the play of doing what we want to with the things that we have, and finally reflecting and evolving the solution at hand either with better ideas or new or new ways of using resources.

- Designing a pedagogy must ensure that these aspects of exploration, solving and evolving. Still, at the same time, the learners can do them in any sequence and manner they want.

Xperseve allows the structuring of activities; hence one may adapt activities that focus on one of the three aspects but allow them to do any of the three at any given time. This can also be achieved by dividing the time of the entire problem-solving activity. One crucial thing the pedagogy must ensure is the opportunity for the learners to reflect as and when they do each.

Role of Mentor: Mentor is one of the most important aspects of a learning environment, and the reason we use the term mentor is that they play the role of a non-contributing participant in the session. They are as involved as the participant in problem-solving yet do not directly contribute to the solution process. They act as a safety net under which the learners can work as they please, but to ensure that they do end up tinkering and not hurting themselves, the mentor has to be as involved in their solving process as the learners.

- The mentors must have worked on problems with resources available in the environment and worked on as many solutions as possible. This is essential to understand what the learners are doing and heading into and when or where the mentor should intervene. In no sense does it mean that the mentor will know of every possible method or solution, but they will be able to develop an understanding of it.
- One of the most important aspects of a mentor's role is to trigger reflections. The mentor can guide them into a reflection by asking them questions or making them challenge their ideas and actions. The mentor should interact with the learner as a curious observer through questions. Reflections can be triggered by asking questions about their current actions, their trajectory, their ideas, their intuitions or the challenges they are facing. Reflection can also be triggered with analogies from experiences of the learner's daily life parallel to their existing ideas or actions that force them to think or challenge their ideas and actions. Triggering reflections is one way a mentor can guide and even direct a learner out of challenges and allow them to understand actions and phenomena that have happened, leading them towards a solution.
- Mentors can also interact with the learners by keeping checks and prompting them to do something. The checks can be time checks to keep the learners stay on track if they have spent much time in undirected play, which can again be in the forms of questions about their progress and their estimate of how close they are to solving the problem or on the

contrary allowing them rain checks towards the solution. Hence, they involve themselves in some undirected play or explorations. Prompts can be used when learners show inhibition or much confusion when deciding or performing an action. These prompts act as friendly nudges to get the learners to act or pick something and then think based on their responses to their actions or choices. These could vary from asking the learners to observe something specific, followed by a reflection question, to asking the learner to just try something out instead of speculation. Prompts also allow learners to switch to the overall objective when the learners are lost in the details.

- Another critical aspect of the role of a mentor is to provide operational information with ease themselves or offer mediums to the learners that allow them to locate and get operational information with ease. This could vary from directly providing the learners with the information or guiding them to the media through which they can locate it quickly as and when required.
- Lastly, one of the essential aspects that a mentor must ensure the learner always has a sense of agency, and to do so is to know when to reassure and when to refrain from intervening with the solution process of the learner. This is important for the learners not to be able to handle being stuck or experiencing failure. If the learners seem to be following a path that may lead them to failure, the mentor may make them reflect on their actions, and yet if the learners seem to want to or choose to continue on the same path, the mentor may abstain from intervening. Suppose the path leads to failure, as expected by the mentor. In that case, it is an important opportunity for the learner to experience it, and the mentor then gets the learner to reflect and look at the failure as an alternate possibility or like an alternate reality. If the mentor is still determining the outcome of the solution path, the mentor may choose not to intervene and let the outcome present and ensure they make the learners reflect as it reinforces their actions and ideas. On the contrary, if a learner seems unsure or scared to take a path that might lead to failure, the mentor must reassure the learner to try things and look at failures as opportunities and alternatives. The mentors, at all times, must ensure their role as the safety net and intervene in any learner's action that may lead to physical or mental harm.

Scaffolds: To make the learners explore the learning environment, they should provide scaffolds that encourage them to interact and perform actions with the physical resources.

- One way of scaffolding exploration is by providing the learners with objects made out of resources one can refer to, use and manipulate. They become the memory of the affordances and uses of resources. These examples demonstrate the use of resources and their affordances and could have some alignment with the possible solutions to the problems.
- The tinkerability of resources has to be ensured, which means the resources should provide immediate feedback and allow fluid experimentation and open exploration (Resnick & Robinson, 2017).
- The resources should be arranged to make the resource search process efficient. One may choose to arrange the resources based on a set of characteristics that can be aligned with the need of the problem. Functional affordances are characteristic of arrangement for problems that require the solution to achieve a function, and if the problem requires a structural solution, the arrangement could be structural. They can even have a hierarchy where one characteristic is used for major classification as the minor.
- Demos: Situate demos of important resources like programming environments or tools that aid problem-solving, like serial monitors, in the context of the problems or the domain in which the problem has been given, allowing learners to understand their usage and build an association. Providing enough example solutions to similar problems could help overcome design fixation.

The design guidelines can be used to build adaptations of Tinkery 2.0 or more extensive learning environments. These can also be adopted for designing learning environments where tinkering is a part of the learning activities while focusing on conceptual learning in a specified domain.

Who can benefit: The identification of the design guidelines is a piece of valuable knowledge for researchers who would be interested in the creation of learning environments that scaffold tinkering-based problem-solving. The instructors who want to expose or train learners on the use of tinkering for problem-solving in various topics and domains of engineering design, given the availability of relevant building resources. Researchers can also create variations of Tinkery 2.0 by implementing the design guidelines for new problems or resources.

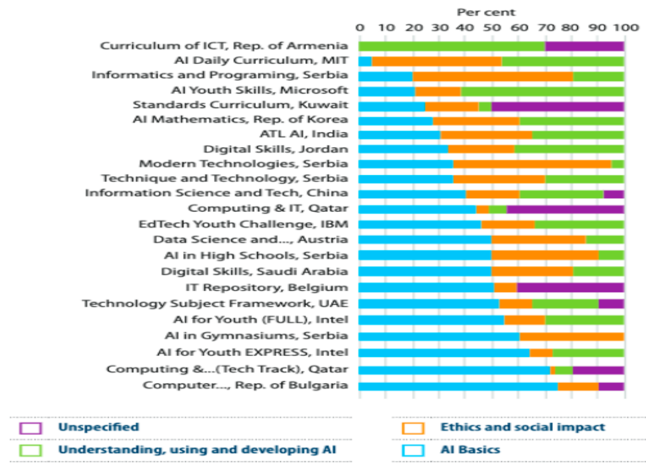
8.2 Additional Explorations

The following explorations resulted from a spinoff of our primary research objective. They were considered additional as they were separate from the research design due to time and operational constraints. They were emergent throughout the process of designing the pedagogy and Tinkery.

8.2.1 Secondary Implementation of Pedagogy (Xpresev)

Explorations for designing Tinkery 2.0 and its pedagogical basis aided the design of three modules for teaching and learning artificial intelligence using tinkering for the ATAL tinker labs (NITI Aayog Govt of India, 2019), part of the Atal innovation mission of NITI Aayog, Govt of India. The module's broad objective was to allow learners to choose their learning path and support them if they fail. To ensure the development of the modules with *progressive formalisation* by presenting the concepts gradually, and the activities were *situated in a real-life context,* arguments were provided along with *analogical scenarios, and* activities were designed to encourage *play* with the entire learning experience designed around *tinkering* to solve problems which were *scaffolded* with examples, resources and mentor interventions.

The three modules are available at https://aim.gov.in/Let's_learn_AI_Base_Module.pdf (Based Module), https://aim.gov.in/Let's_learn_AI_StepUp_Module.pdf (Step up module) and https://aim.gov.in/Let's_learn_AI_StepUp_Projects.pdf the projects module. All such modules developed by the various government organisations of the world were evaluated by UNESCO, and based on their results, it was observed that the ATL modules from India were found to be balanced in terms of conceptual understanding of AI basics, using and developing an understanding of AI based on activities and finally the roles of Ethics in AI (UNESCO, 2022).



Source: UNESCO (2021*b*)

Figure 8.1: Content distribution among basics, activities and ethics in AI modules of various nations.

8.2.2 Tinker Bot

TinkerBot is a Slack API-based chatbot primarily designed to assist mentor-participant interactions in a workshop setting in a semi-automated manner. Mentors can prompt, trigger and check on participant progress in a partially-automated way in a conversational mode. TinkerBot provides the participants with an interactive logging journal. It allows them to see the problem statement and required resources during a workshop and ask for mentor interaction on the same platform. TinkerBot can maintain participant states by monitoring their activity remotely, allowing a mentor to be engaged with multiple participants simultaneously. Timing prompts based on activity duration and sequencing can offload mentor checks and provide information resources in an automated manner. So, a TinkerBot mentor can keep a bird-eye view of the participants and get seamlessly involved with them. The TinkerBot has three major components: the Slack API infrastructure, Data Store and Scaffolding Logic. A scaffolding logic governs the automated and semi-automated prompts and triggers given based on the progression of the participant in a given challenge from their logs or by time-based events or based on the participant's activity on the app or prompts explicitly sent by the mentor seen in Fig. 8.2. When a new participant is registered, TinkerBot sends an interactive message as shown in Fig. 8.3 (a), it introduces all the components of the LEGO Mindstorm Kit. The messages are written with emojis and use the pronoun "we" to make it seem like a friendly companion. Fig. 8.3 (b) shows the routine after the generic introduction: TinkerBot waits for the participant to go through the shared resources, after which the participant hits "Ready", implying they are ready for their first challenge, and then the bot would send the problem statement along with the other detailed resources required to solve the problem. We have added a few intuitive commands for both participant and mentor. Fig. 8.3 (b) shows the commands that can be used by a participant, like “help” and “ask-mentor”. “Help” can be used to display the list of commands, and when a participant sends the “ask-mentor” command, the mentor is notified through a different channel on Slack so that they can join and help the participant. A few commands like “resources” and “task” are shared between the mentor and participant, and the mentor also has other advanced commands. Fig. 8.3(c) shows the form to add a log to the participant's journal; if the participant wants, they can also add pictures by attaching files in the chat. Fig.8.3(d) shows another form, which is for the mentor to select the participant’s next task(challenge). Depending on the participant's progress, he/she can select from the list or create a custom challenge.

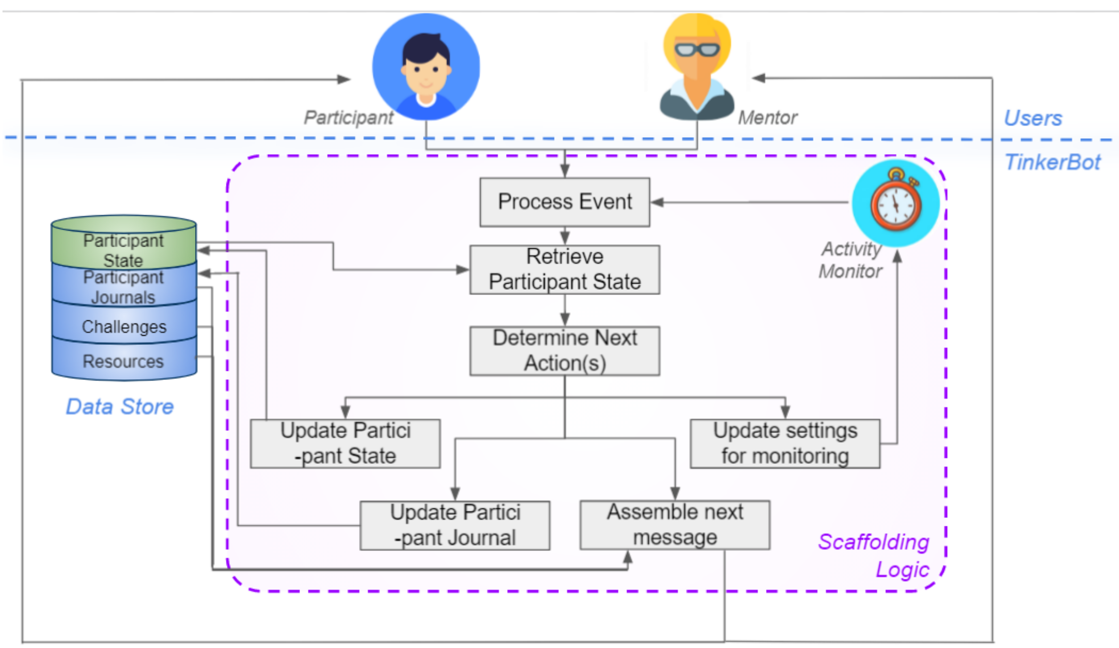
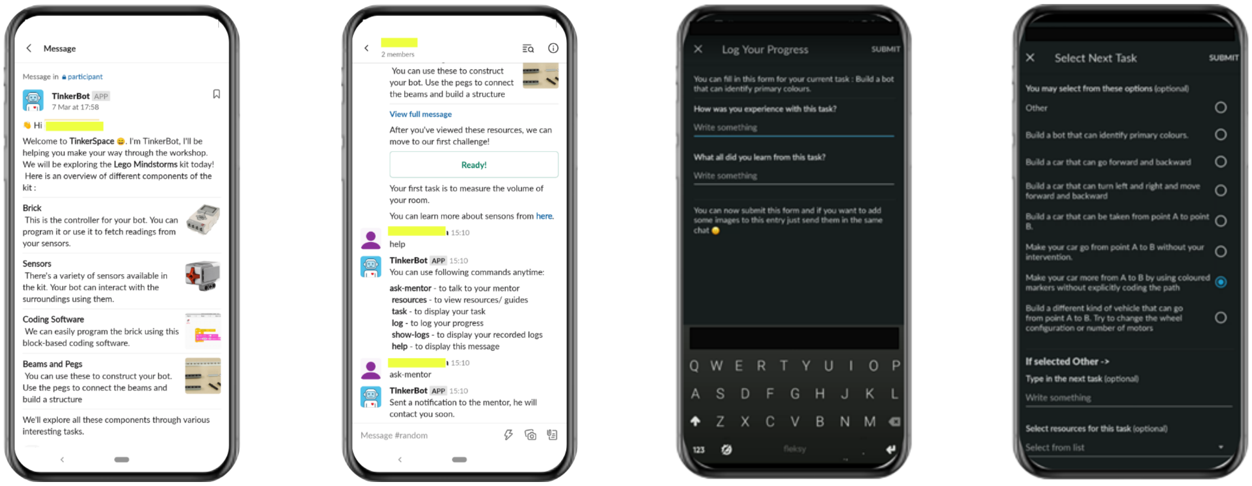


Figure 8.2: Scaffolding logic and it’s interaction with Users, Data Store and Monitoring App



(a) (b) (c) (d)

Figure 8.3: (a) Interactive introductory message received by the participant. (b) Participant can discuss with mentor on same platform. (c) Forms to create a logging journal. (d) Mentor can select next challenge from the list or can create a custom challenge

In this exploration, we attempted to understand the process of solving a challenge and analysed mentor-participant interaction, and we identified events that initiate a conversation between mentor and participant and classified different types of prompts given by the mentor. These states, events and prompts helped us develop conversation routines which were coded into the chatbot in the form of decision trees. While a mentor is irreplaceable, developing a hybrid model can be very efficient as a mentor's presence is limited. Chatbots conversational nature can allow it to act as a companion, which is limited to a mentor. Through TinkerBot, a single mentor can manage multiple participants, especially helping the mentor offload various tasks.

8.2.3 Tink-Mate

This exploration was carried out to address the challenges of seamless information exchange for which we propose to design a tinkering companion for engineering design kits, namely Tink-Mate, a mobile phone-based platform which provides information and triggers as and when required via two seamless mediums of interaction as shown in Fig.8.4. Firstly it will use a tiny robot as a physical pedagogical agent (PPA) that sits on a work table allowing the user and Tink-Mate to interact using speech and image recognition capabilities vocally. E.g., instruction from the PPA saying, "Start simple and start making?" to encourage constructing with the first simple idea. It would also provide behavioural triggers like expressions and human-like body motion, as seen in Fig. 8.5. Secondly, Tink-Mate's phone-based augmented reality (AR) feature would augment information about the kit's components to ease their exploration and experimentation. E.g., Information about the use and configuration of a sensor, like its pinout diagram, voltages, and frequencies, provided by augmenting it over and around the device. We conducted a contextual inquiry to identify features for a seamless interactive tinkering companion that would support users with information essential for engineering design problems without searching for it extensively. We aimed to develop an initial proof of concept for Tink-Mate, for which we considered getting an off-the-shelf educational robot. We surveyed all the available candidate options from different manufacturers in a similar price range based on the features discussed above and small form factor to ensure its subtle presence in the working environment with freedom to obtain the data from the robot and program its behaviour using an API. COZMO by Anki Technologies as it satisfies all the criteria mentioned above. Even though further exploration, we realised that the extent of time and behavioural research exploration would be required to do justice to the affordances of such a robot; hence we chose to keep it as an additional exploration as an option of being able to use it as an expressive learning agent.

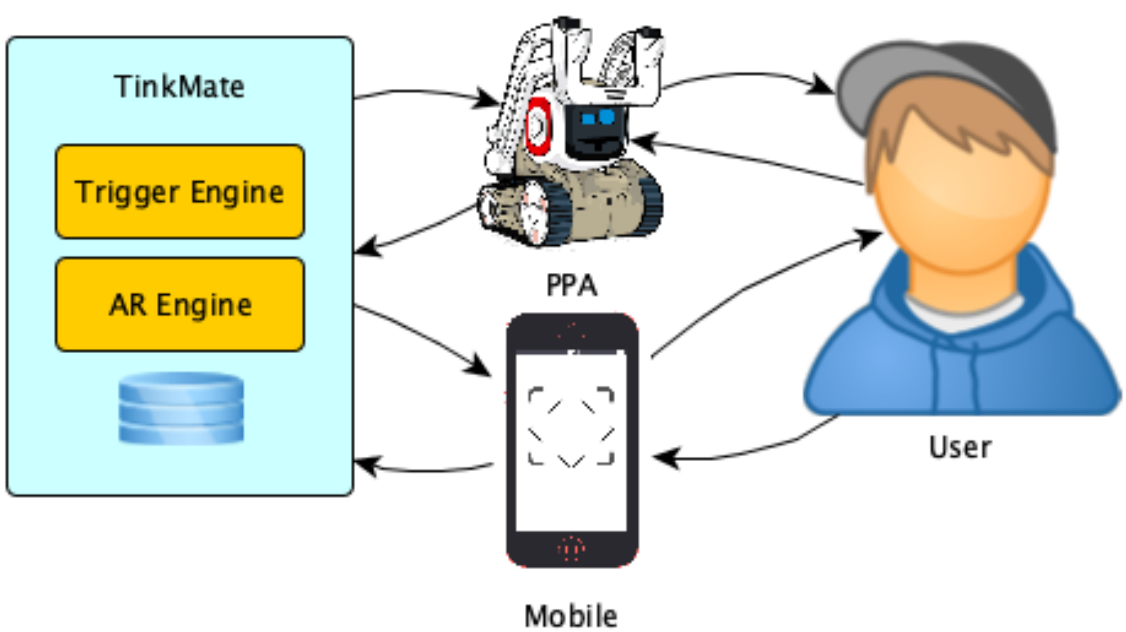


Figure 8.4: Overview of seamless interactions between Tink mate and the user

Figure 8.5: Features of a physical pedagogical agent (COZMO) that would enable seamless interaction between TinkMate and the user.

8.3 Future Work and Extension

In this section, we present possibilities for future work that are various solutions either as a way to address the limitations of this thesis or to extend the research agenda of this thesis.

8.3.1 Application of Design Guidelines for Various Adaptations of Tinkery 2.0

This research looked at the possibility of designing a learning environment that nurtures tinkering for problem-solving. Based on our initial explorations of experts and best practices from the literature, we framed guidelines for designing such a learning environment. We used them to design our learning environment, Tinkery 2.0. Our evaluation found that Tinkery 2.0, an instance of the design guidelines, got the participants to tinker. Though the same may / may not be claimed for another LE designed by making variations of Tinkery 2.0 as per the guidelines, the completeness of the guidelines has yet to be evaluated. Hence there is much scope for designing new LE based on the guidelines. Once we have some learning environments, the guidelines could be evaluated for completeness and later be used as a manual for LE design.

Similarly, for the sake of uniformity, the researcher who was the mentor in the initial study continued to be the mentor throughout all the later studies. The mentor was working as per the guidelines in the various roles mentioned. There is much scope in designing and developing mentor training models based on these guidelines and eventually evaluating the trainees. As of now, the guidelines are just as best practices.

8.3.2 Evaluation of Learning from Tinkering-Based Problem-Solving Approaches.

Our research focused on nurturing tinkering, and the gains observed in conceptual knowledge have been emergent. Tinkery 2.0 or its variations per guidelines can be used in any problem-based or project-based learning setup with additional reflection prompts on changes in their conceptual knowledge. They can be used for teaching and learning of domain knowledge. Researchers may further use such setups to understand learners' interactions with the content and evaluate the gain of conceptual knowledge to add or modify the guidelines where the primary focus can be conceptual learning with problem-solving.

8.3.3 Role of Collaborations in Tinkering and Designing Support.

Tinkering has been considered and seen by experts as a majorly individual activity (Louridas, 1999). Understanding of tinkering in itself has been a very varied and context-dependent life for problem-solving vs for learning; hence we choose not to add collaboration. Recent literature has reported tinkering and evaluated it immensely in collaborative frameworks to show signs of learning and its advantages in a collaborative environment. More research needs to understand the progression and variations in the thinking processes when done individually or in an active collaborative setting. The question that arises is how problem-solving or learning in tinkering-based LEs is influenced by collaboration. Is there a need for mediation of one in the presence of the other? What features/factors could be used to mediate and ensure both complement each other rather than just create chaos (Adamson & Walker, 2011)**?**

8.3.4 Tinkering for Problems in Non-physical (Simulation) Environments

Scratch (Resnick & Robinson, 2017), a block-based programming language, has been designed on the principles of tinkerability. It has been extensively explored for teaching and learning programming in various project and problem-based settings (Zhang & Nouri, 2019). This brings us to the question: Can similar software-based environments that subscribe to tinkerability also be used to teach and learn skills like computer architecture, network design, network troubleshooting, etc., using tinkering-based activities? If so, then further analyse the role tinkering plays in learning such domain-based concepts or skills. For computer networks, several off-the-shelf platforms like Cisco packet tracer or GNS could be used to work with network design scenarios and troubleshooting.

8.3.5 Extensions to Other Domains

Possibilities of using such LEs for problem-solving are not limited to engineering design, and one may explore other domains of science, maths and arts (Bevan et al., 2015). Tinkering in literature has been associated with scientific discovery (Kantorovich, 1993) and various domains of medical sciences (Knowles, 1987; Mol et al., 2015). Similar instances are available in the domain of art (Lewis & Thurman, 2019), where tinkering has been used as a medium to foster creativity (Rognoli & Parisi, 2021), and in the domains of humanities, tinkering was embedded into inquiry-based activities (Wargo, 2018). Hence there are vast possibilities for exploring the role of tinkering-based activities and LEs in various domains where learners take agency in their learning and problem-solving process. With scaffolds in the form of conceptual and metacognitive prompts, reflection can expose the learners to gain a conceptual understanding and their learning processes. Researchers from various domains can use the inferences from the experts, literature-based best parties and guidelines from this thesis as the basis and start building activities or LEs to analyse further and evaluate the role and impact of tinkering-based learning activities.

8.4 Final Reflections

This thesis's genesis came from my early experiences of learning to code in Visual Basic. I found it much easier to start a solution design from a half-done program and evolve it how I wanted. I sometimes consider that a shortcut in contrast to the general notion of a systematic design process. Since then, it has been a part of my process of solving engineering design problems for a very long time without a clear realisation of tinkering. Two years prior to the start of this thesis, I started exploring the processes of tinkering. This thesis has attempted to understand tinkering from the problem-solving perspective in engineering design. There has been extensive exploration for learning with tinkering but not much on problem-solving in an individual setting. Hence this thesis can offer some insight into individualistic problem-solving with recommendations for incorporating and supporting (nurturing) tinkering for problem-solving extendable to learning. Through this thesis, we understood tinkering as a mix of goals, processes, orientations and activities. We define it as evolving a solution by building experiences of exploration and play. Tinkering has become an authentic practice in engineering design, like a tool in one's problem-solving tool kit, especially for ill-structured problems. However, its efficiency, robustness, etc., comparison is up for debate.

On a personal level, I have been thrilled as I have come to understand and realise the role situatedness and physicality play when tinkering to solve problems, as they allow actions on externalised ideas, reducing the cognitive load of remembering, tracking and processing several aspects of an idea. What seems meaningless wandering with random pieces leads to opportunities for new ideas to emerge. Now I can comprehend how people working on the ground in the context can arrive at innovative and frugal solutions to complex problems.

Looking back on my PhD, I find that this thesis has arrived at its conclusion: starting from a broad problem space, exploration and collation of literature, discovering the nuances of tinkering in the voices of the seasoned tinkerers which led me to derive the guidelines and design and evolve a learning environment. This process is at the heart of educational design research, allowing the researcher the space and time to explore and refine. This journey has been beneficial to me, allowing me to grow as a researcher, and to learn to be patient and sensitive, acknowledge the ground realities and keep an eye out for the unexpected - tinkering my way into engineering education research and emerging with enriching experiences, grounded understanding and this thesis.

Having written up about the exploration and play with tinkering in the past six years makes me realise that it is just the beginning. I want to contribute to further explorations and learning because this thesis is just a peg in the broad structure of what tinkering is.

Appendix A

Complete Findings for Conjectures

A.1 DBR1

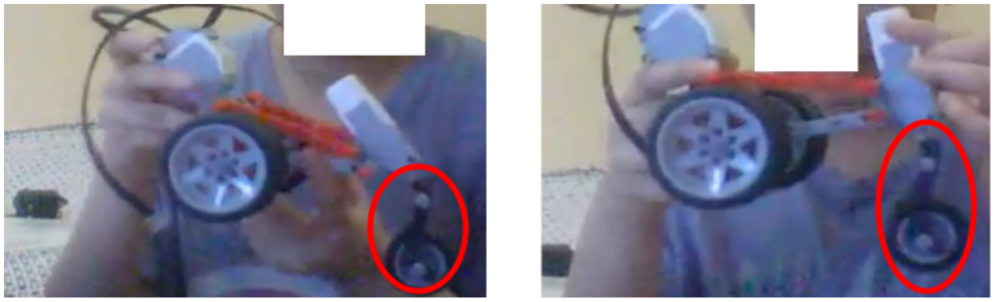
A.1.1 Findings for Design Conjectures on Scaffolding:-

- **DC4:** Access to resources displayed according to Lego reference cards supports learners in performing actions on built artefacts to seek feedback, using materials in their own ways and developing workarounds.

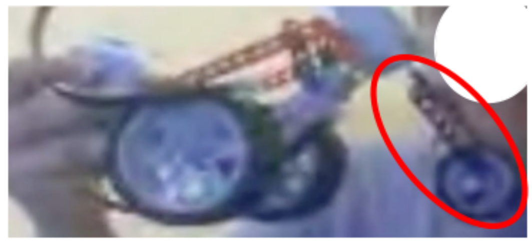
  In the following observation participant 3 is trying to build a bot in the form of a tricycle. The back wheels have a separate motor and the front wheel has a motor on top to turn the wheel to make the bot turn. The challenge is with the connection of the motor with the front wheel. The learner has found a piece that connects to the motor and allows connecting an axle bar to it. The learner has connected the axle bar to two beams but the beams have a circular port that allows the axle to rotate freely. This is desirable in case a wheel is connected as we would want the wheel to rotate freely but here this is joint to the beams that hold the wheel which will have to be sturdy. As we see in Fig. 5.7 the beams holding the wheels are free and swing like a pendulum. She is trying to provide support so that the structure does not sewey. This is the point from which the observation has been taken.

  Episode 4.2 : *The mentor suggests "now that you know how you want to build the front wheel you could look for different parts and and see how you can reduce the number of parts currently you have used to make it more steady" The mentor then points towards the cards on the box that show all the pieces that are available in the kit. She picks the cards and looks at them. The participant points out a piece and says "could this be useful ?" To this question the mentor takes a different approach and asks "What are the things you are looking for? What are the things that you want in the piece?" To which the participant replies "I need a piece that has a crisscrossing circle and should be a bit long on the top* *then in that case I won't need so many connections on the front of the bot". She is seen looking at the pieces on the cardboard for some time. The mentor then suggests a strategy to search for the pieces. The mentor suggests "let's first look for the pieces that are long and then see if any of the long pieces have a circle and a cross joint". Based on that the participant looks for a piece on the cardboard and finds one. Then she says "I think this should work, should I try it?" to which the mentor says "Sure you may". After a bit of a struggle among the trays she is able to locate the piece. Then the participant removes the extensive connections and just uses the new piece found and connects the wheels and the motors.*

Here the mentor guides the participant first to reflect on what the participant expects the structure to do and then what the piece she is searching for the structure should do. To which she is able to determine that if there is a beam which has a cross port at one end it might keep the wheel holding structure steady. The mentor then guides her with a strategy to look for components as the number of components seem daunting to her as she is unable to devise for herself a way of looking for components.



Learners using a beams and axles to connect the front wheel to the motor. The choice of beams makes the joint free and front wheel is not steady.



With mentors nudge and the resource cards available the learner is able to find a different beam that has cross ports at one end not allowing the axle joint to move freely but circular on the other allowing the wheel to move freely.

Figure A.1: Reference cards allow learners to find a new component and workaround the challenge she was facing.

The basis of this strategy is a methodological search into the components based on knowing what the requirement is and then a visual search for those features. This search is made possible as the components are depicted on the reference card and also arranged as per the way they are seen on the reference cards. This allows her to spot a beam that has a cross section port on one end and a circular port on the other. The arrangement as per the reference cards and using the reference card with the nudge from the mentor allowed the learner to find a new component based on an affordance she was looking for and hence develop a workaround for building support into the front wheel while continuing to build the solution she wanted to build. Many more similar instances were observed where learners were able to discover new components from the cards like various beams, pegs and in one case a castor wheel to be able workaround a challenge they were facing.

A.1.2 Findings for Design Conjectures on Problems:-

- **DC5:** A set of problems ordered based on complexity eases learners into engaging in playful exploration.

The following observations are from participant 4 trying to solve the problems of calculating the volume of the room and detecting the colour on day one and making the vehicle navigate autonomously on day 3.

episode 5.1 *Participant asks the mentor "Is there an option for a serial monitor?" The mentor says "yes and you should explore the options available in the brick". He tries to figure out and finds it and then tries to use the options in the IR proximity sensor. This option allows him to look at the values the IR sensor provides when pointed to a given direction. He observes and then says "There is a lot of variation on a similar distance" and soon gives up the IR sensor. He continues the search when he finds the Ultrasonic sensor and says "this is the right one!". The participant says "I can tell how I am going to do the calculation" to which the mentor says "go ahead and calculate it and tell me the distances". As he tries to calculate he realises there is some error as the distance that the sensor reports does not seem like the dimensions of the room. He continues the playful exploration and eventually realises that the sensor has a max limit and the room is longer than the limit. To overcome that he then measures the dimensions of the tiles on the floor and eventually calculates the area. Similarly he measures the door height and the height of the remaining wall to the roof to get the volume .*

For the second challenge he says "The ultrasonic distance sensor will not help in differentiating colour". He checks the other sensors and picks a sensor and says "This has an LED and a receiver that could do some reflection stuff ". So he connects it to the serial monitor and using the centre button tries to figure out the different options available with the sensor. He chooses the IR setting and sees there are changes in values in the reflection *option but then he says "Values are not very distinct for a set of colours" so he looks for more options and eventually finds out the colour detection option.*

- *Later during the third session on the third day.*

When given the autonomous moving bot problem he says "The idea that comes to my mind is I could use the ultrasonic sensor and the colour detection sensor in tandem to make the bot avoid obstacles and give instructions based on colour codes for turns." Eventually he built the bot this way.

Here we see that the first two problems required the learners to focus on one component affordance like the use and characteristics of an ultrasonic sensor and its differentiation from a proximity IR sensor. The first problem pushed the learner to playfully explore one sensor which is the ultrasonic and just one affordance of it which was measuring the distance to calculate the volume of the room.

In the second problem the participant is now required to playfully explore the reflection sensor with its multiple affordances which are IR reflection, proximity, colour, reflection etc. He had to try various options before he could determine which function (affordance) of the sensor he could use to solve the problem. There is a gradual increase in the complexity of the search by trying to figure out the correct affordance among multiple affordances of the reflection based sensor that works for IR as well as RGB. These initial challenges allowed the learner to focus on components and playfully explore as the correct affordance could be directly used to solve the problem. Through this search the learners get to know about how these components can be used.

On day three the participant is aware of the possibilities of the sensors and now has to focus on how to solve the problem as the solution requires a combined use of both the sensors. Here the playful exploration is among the ideas that he has for making the bot autonomous and the affordances of the sensors that he is aware of. Now the focus is on the problem as the solution is not just the choice of an affordance but using a number of resources and some of its specific affordances together to achieve a solution. As he states he could use the ultrasonic sensor to detect the distance between obstacles and then use the colour as codes for the bot to take a turn. These ideas though seemed simple, execution had a lot of challenges like should the code be based on sequence of events or just a parallel execution. So playful exploration was carried out to make decisions on such factors.

Hence the ordered set of problems initially force learners towards playful exploration with resource affordances and as the problems progress the playful exploration then leads to playfully exploring ideas as solutions that could be achieved with a number of single affordance resources like motors. Eventually mapping resources affordances with solution ideas becomes the objective of playful exploration. This gradual change in the way playful exploration complicates allows the learner to remain engaged initially focusing on either affordance or ideas and they then move towards playing with the resources to realise their ideas. Similar observations were made with all the other participants. Though there were differences in the way they built their bots or even coded their autonomous bot their initial explorations of resources were similar and the variation arose as they progressed into the problems requiring them to playfully explore their own ideas. Hence we can conclude that an ordered set of problems allows learners to remain engaged in playful explorations rather eases them into it as the complexity of problems and their explorations increases.

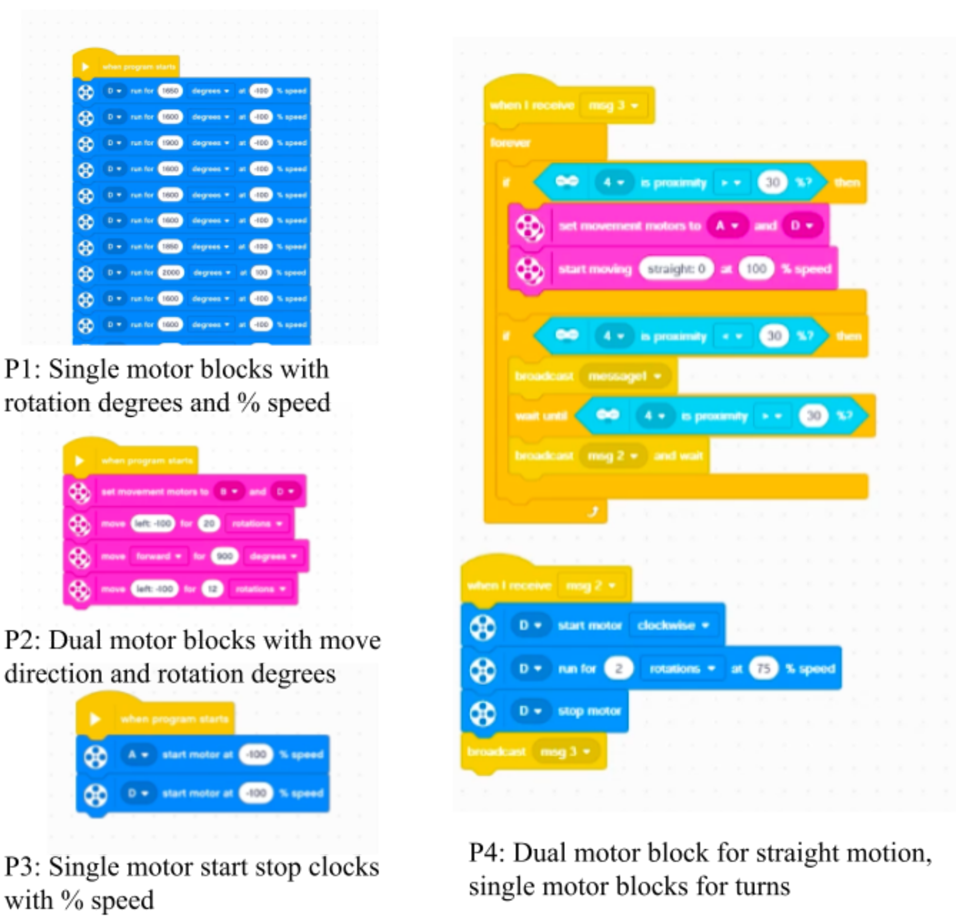
- **DC7:** Open-ended design problems allow learners to use materials in their own ways

Participant 1 on day two of the workshop is to build a robot that can go from point a to point b. Here she is in the initial phase where she is talking about the possibilities of bots she could build.

episode 7.1: *She starts thinking about different ways the robot would be made. Her initial idea is "I could build a robot which can detect and avoid obstacles which is what I have found based on the search on google and a few research papers that talk about the use of ultrasonic sensors to avoid obstacles." She starts with this approach and is seen trying to figure out a way of using ultrasonic sensors. She even searches for "using Lego mind storm to make an obstacle avoidance robot". The mentor interrupts and asks "So what have you decided as your initial approach to solve the problem". So she says "my idea is to detect obstacles using ultrasonic sensors but I am not sure how the robot should react* *when it detects an obstacle". The participant continues to explore and after some time when the participant has not built something new or coded someint the mentor asks a reflection question. "Let's look at what the problem is, the robot is supposed to go from point A to point B and we know where the points are so how is an obstacle avoidance system helping the robot to go from point A to point B?" The participant thinks for a while and responds, "If the robot knows where the obstacles are and knows how to go from point A to point B then it can be done without an obstacle avoidance system". The mentor says "okay then you could try to find a way in which the robot knows how to get from point A to point B". . . . . Eventually she figures out she could just hard code a path by hard coding the why the bot behaves i.e go straight for a given distance and then turn at a given angle and then move. Even there she has a number of choices as she could use degrees of rotation as the function or number of rotation as the function or the duration the motor runs at a given speed. She chooses the number of degrees as it allows her to do a calculation based on the number of degrees of rotation required to cross one floor tile and then use its multiples to reach from A to B . . . . . As she is to solve the autonomous bot challenge on day 3 she says " Oh now I can use the colour sensor to instruct the bot to turn a particular way and use those colour indicators to avoid the obstacle".*

Here we see that the problem of going from A to B is open as the learner is able to think of solving the problem in different ways, one on her own and one with the nudge from the mentor. In this particular scenario though the problem can be solved in a number of ways but in the current state based on the requirement of the problem, the current solution idea seems to come from her recent exploration of the ultrasonic sensor. As she was spending a lot of time to figure out what to do when an obstacle comes it seemed to be a complex approach to the mentor as the participant is trying to figure out both the aspects together i.e. is going from point A to B and avoiding obstacles hence the mentor intervened with a reflection question to allow her to choose and solve one of the challenges at a time. To do so, given the open-ended nature of the problem, the mentor makes her reflect on the primary challenge she has to solve. With this reflection question she chose to start with the problem of going from point A to point B.

She figures out a way of solving the problem by hardcoding the path. She has a number of choices to hard-code the path for which she chose to control both motors independently and use the total number of degrees the wheels rotate as she had found the number taken to travel one floor tile. She used that as a reference to figure out the distances she had to go straight or when she had to take a turn as seen in code block of participant 1 in Fig. 5.9 . Eventually by day three the problem required her to build the autonomous bot and by then she already knew how with combination of going straight and taking turns with hard coding she could avoid an obstacle so she chose to use the colour detection sensors to code the obstacle avoidance blocks and labelled the obstacles with the relevant colours.



P1: Single motor blocks with rotation degrees and % speed

P2: Dual motor blocks with move direction and rotation degrees

P3: Single motor start stop clocks with % speed

P4: Dual motor block for straight motion, single motor blocks for turns

Figure A.2: Different functional blocks used to achieve forward motion and turns.

When we look at the process other participants used to develop their solutions or if we compare the solutions themselves we see there are slight variations like the way in which participants choose to hard code their bot to go on a specified path using various combinations of number of degrees to rotate, number of rotations, speed, duration and direction. This also varied in terms of the number of motors that were being controlled like P1 and P3 chose to code two the motors individually and execute the blocks in parallel for both the motors. P2 chose to code using the combined motor block executing them sequentially. Whereas P4 chooses a combination of both using combined block for straight motion and individual blocks but in serial execution for turns as can be seen in Fig. 5.9. Interestingly the solution (for problem 2) for P1 (two motor castor wheel) and P3 (tricycle bot) were very different even when their programming approach was similar and solutions design of P1 and P4 (two motor castor wheel) were similar but both had a very different programming approach as seen in Fig. 5.10. Whereas P2 with a four wheel controlling two motors had a completely different solution approach for designing and even programming approach was a bit similar to that of P4. Additionally P4 out of all the participants choose to program the bot as an obstacle avoidance robot from the beginning rather than hard coding the bot to get from A to B.

- **DC9**: Open-ended design problems help learners consider failed attempts as opportunities to try new creative approaches.

This observation is a detailed version of what we presented in the last part of observation 6.1 where participant 2 is trying to figure out how to make her four wheel bot run straight and turn when just using two diagonally opposite wheels.

episode 9.1: *She now chooses to code the diagonal two wheels to run the bot. She uses the set movement block setting the motors on ports B and D as movement motors (ports at which the diagonally opposite motors are connected). To move straight she initially codes the motors to move forward. The bot does not move forward. So she uses the code to move left for 5 rotations. She is surprised when the bot moves forward. She says "ok! This does not make sense" and looks at the mentor, to which the mentor says "but If you can control it this way just use this". She says "Ya i can" and starts to figure out an estimate on the number of rotations based on how far the bot travelled on the tile. As the bot is able to move forward now she has to make the bot turn. To do so she adds the move forward block* *again and there is no response from the bot. She observes that there was a minor jerk. When she lifts the bot up she observes the wheels start moving in opposite directions but when she keeps them down they just seem to just give a jerk and not move. Then she says "oh as the motors are inverted that's why turning left is making the bot go forward and forward is making the wheels turn in opposite directions. Hmm but now I think I will have to redesign the entire bot to free the other two diagonal wheels from motors as I am not able to control all the four motors at a time". The mentor interrupts and asks "why do you think it is not able to turn?" She says "I feel the wheels are not as free to move as drag wheels". To which the mentor says "Is there a way where you could test this?" She replies "I'll have to remove the motors I guess, Is the rubber tyre on the wheel removable?" to which the mentor replies "yes". So she removes the rubber from one of the tyres as she wants to use both the back tyres to move forward. The bot moves forward perfectly but as it tries to turn one of the rear wheels still shows some resistance. So she decides to remove the rubber from one of the rear wheels also and then test the bot.*

The learner here has the freedom to choose, change and set her own objective which may or may not be specified as requirements but are seem important to her. An open ended problem just requiring the participant to go from point A to point B allows them to choose the structure or the controlling mechanism of the bot. Before the participant decided to hard code she had chosen to use the brick buttons as remote but as she was facing an issue she was introduced to the Lego commander app and used that instead to control the bot. Here the problem gave her the freedom to change the way she wanted to control the bot. After using a remote to manually control the bot she decided to hard-code the bot (presented in observation 6.1) where she again faced a number of challenges in terms of the blocks to use to control the motors initially using individual blocks to control the motor and later choosing to use the movement blocks allowing her to control 2 motors with a single block. In this observation we see that she was able to both move and turn just by using two diagonally opposite wheels as the problem did not constrain her to use all the four wheels. Additionally, based on her statements that she can get the bot to perform as she intended if she is able to control all four motors or if she just removes the two diagonally opposite motors shows the variability in possible approaches. The current design in a way acts as the proof of concept for her mentioned possible approaches. This design has been developed by working around the challenge of controlling all four motors or redesigning it by just controlling two diagonal motors to get the bot from A to B. Hence the opened problem allowed her to creatively reach a solution to get from A to B and also uncover where the challenges lie to be able to solve it the why she wanted. She addressed the challenges in the next session but using only two powered wheels and keeping the other wheels free.

In the next observation (9.2) participant 1 is trying to program the bot to go from point A on the floor to a point B on the floor. To do so she must program the logic for determining the distance the bot is to travel and which can be done in a number of ways like determining for how long should the motor remain on at a given power setting or the number of rotations it must take to reach the point.

episode 9.2: *The distance the bot has to travel can be controlled by the duration the motor remains on at a specific power or by specifying the number of rotations or the degree of rotation. So the participant is in the process of deciding the logic. She first looked at the path the bot was supposed to travel which was on the edges of a tiled floor. So she picks the bot, marks a point on the wheel and on a paper she puts it on. She runs it on the sheet of paper till the point comes back and marks this new point on the sheet. Then she measured the distance between these two points to measure the circumference of the wheel. Then she measured the length of the tile and made an estimate of the number of rotations required to traverse the path, then she looked at the run block and chose degrees. Then she multiplied the no. of rotations she had calculated to 360 and used the number to determine the value. She then tested it out for a straight patch when she observed the bot was neither able to cover the distance nor was it moving in a straight line. She looks at the mentor and says "I guess I did not keep it straight in the beginning hence its not moving in the straight line". She places the pot again making sure it parallel to the lines created by the edges of the floor tiles. This time the bot travels almost in a straight line but stops half a tile short of where it was intended to stop. Participant says "I have checked my calculation. They are right so why is it stopping early?". Mentor responds by saying "Try* *to run the bot again and let us observe what is happening when it starts". So she runs the pot again and looks at it while it starts and stops short again. Then she picks the bot and tries to move it with her hand. Then she says "The wheels are slipping when running on the motor. Especially when the bot starts the wheels slip and it starts with a jerk. So the number of rotations the wheel makes is not as intended." She reprograms the bot to run at 50% power but even now the wheels tend to slip. Then she opens the portview mode on the Lego brick and drags the bot on one tile. See notes the value of degrees in the port view and says "this value is close to what I had calculated". She then programs the bot for the same number of degrees changing the power back to 100% and runs the bot but it still stops short of the entire tile as the tyres can be seen slipping. Then she again switches on the port view and drags the bot for the remaining distance and adds that to her value, then she increases it more by 45 and then executes the command. This time the bot covers the entire tile. Then she recalculates the entire path and runs it and the bot covers the entire stretch. .. . . Later during the reflection interview talking about this episode saying the port view was helpful in making an estimate. She also asked the mentor why the bot was tending to slip to which the mentor picks the bot and shows her the wheels which have gathered some dust to which she says "ohh so this is causing a loss of friction when running on motors as when is was pushing the bot with my hands the wheels were moving properly. Maybe if I would have reduced the power even further that could have helped reduce the slip."*

Here the participant had to get the bot from point A on a tiled floor to point B on the tiled floor. The problem was open to allow them to take any path to go from A to B but the design ensured that it was not a straight line and they had to take at least one turn to get from A to B. Neither were they required to make the bot travel in a straight line. Participant one in this observation took a modular approach to calculate the values to code that would ensure the bot covers an intended path. Being observant allowed her to use the tiles as means of easing this calculation and making it modular. She had not accounted for friction and calculated it for an ideal scenario which became evident with her first trial. The problem neither restricts her to stick to a specified approach nor define a way the bot should be programmed. It was her choice made out of what she believed would work.

With some reflections triggers from the mentors (also supporting the DC 11) she was able to locate the challenge. She changed her approach by finding the degrees by pushing the bot on the floor and observing the number of rotations (in degree values) the wheels made. From what she mentioned in the interview it becomes clear that she was aware that when the bot runs on motors there is loss of friction and wheels slip. So we may claim that she was aware that the bot would travel less than what she was calculating hence in the subsequent run she again found the distance of degrees she bot was landing short by manually pushing it and additionally adding an offset of 45 degrees. Eventually she was able to get the bot to the point. We can consider the use of port-view and manually dragging the bot to estimate the number of degrees to be coded as a new creative approach. Then following this process not just for this section but all the turns and the other section till the bot gets to point B. During the extended episode we saw that the bot did not travel an exact straight or linear path to get to B but did manage to reach B in the final trial. With some more modification it was then able to do it with a linear path. The problem was open enough to accommodate this process of getting to point B.

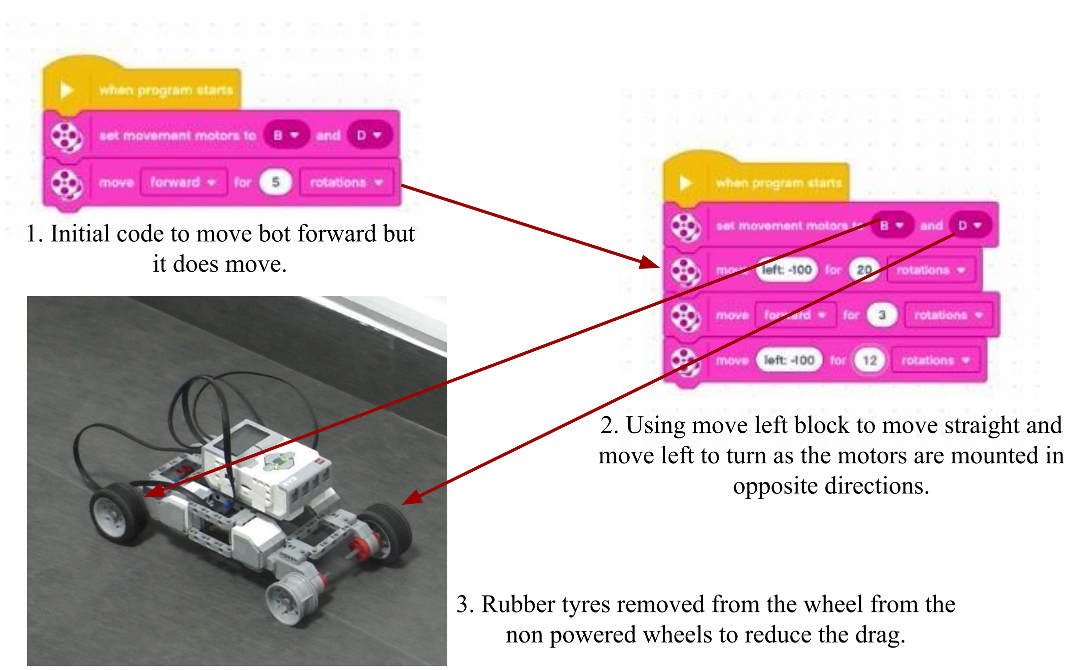
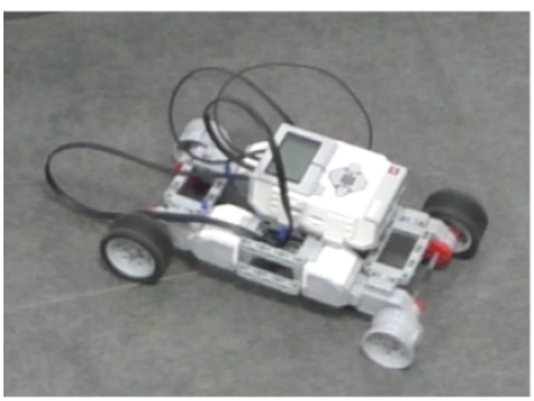


Figure A.3: Changes made in the code by P2 to make her bot move and turn to go from A to B.

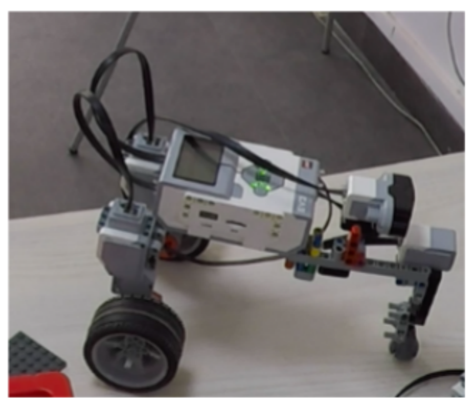
Similarly in a number of other instances with all the participants we see the problems gave them the freedom to overcome challenges by changing the ways they intended to solve it, changing their personal goal in order to solve the problems based on the feedback they receive from the solutions they build and actions they take. Especially if we take the case of P4 who chose to program his bot with an obstacle avoidance logic for the problem of getting the bot from A to B. His bot never took the same path in all its runs as the path was not hard coded but while avoiding obstacles always managed to reach point B and stop. The open ended nature of the problem allows the participants to do this allowing them to reach a solution that is of their making.

P1: Castor wheel based two motor solution

P2: Tri cycle based two motor solution



P3: 4 wheel 4 motor based solution



P4: Castor wheel based 2 motor solution

Figure A.4: Various solutions for problem requiring the bot to go from point A to point B.

With the above mentioned cases of certain variability and certain similarity among the participants we can say that the open ended problem statements not only allows the learner to think of multiple ways of solving the problems, it also allows them to solve the problems gradually from simpler to complex ways and eventually accommodates their choices for building their desired solution. We do see that the problems allow learners to take the approaches they desire and solutions show some variability yet it seems the problem did not have enough variables for learners to control hence we did not find any strong evidence for **DC8**. Later in the challenges we discuss by having huge variation or allowing complexity in solutions one can allow learners to accommodate their ideas better and allow them to build an association.

A.1.3 Findings for Design Conjectures on Mentor Roles:-

- **DC10:** Reflections triggered with questions direct learners to engage in playful exploration and perform actions on built artefacts to seek feedback.

In the following observation the participant 2 is trying to get the bot from A to B as we also saw in observation 6.1. This following observation is from when she was trying to control the front two wheels and move them in opposite directions to make the bot turn. The bot would not turn and then the following happened.

episode 10.1: *The mentor questions "How do you plan to make the turn happen now?". She responds "Maybe by changing the steering mechanism to something else." The mentor looks at the bot, takes a pause and replies "Sure, but can you think of any idea where you use the current steering mechanism but the bot is able to turn?". The participant continues to look at the bot and says "The rear wheels are dragging so I am not sure". The mentor asks her to manually rotate the wheels. As she does it the mentor says "Where do you think the centre of rotation or the rotation axis is when compared to when you were turning the bot with the remote?". She observes the bot and says "The turning axis will have to be at the centre of the bot". She continues to look at the bot for some time and then says "If I am able to control all the four motors at the same time I* *might be able to do that". The mentor says "yes, but can you do it with the 2 motors?". She continues to look at the bot and turns it again with her hands and says "If I turn the diagonally opposite wheels that should be enough to turn the bot."*

The questions from the mentor trigger the participants previous experience with the bot when she was controlling it with the remote control app from the phone and she was able to make the bot turn as the app allowed control over all the four wheels. The reflection question asking her to refer to the previous experience triggers her to a realisation that an all wheel turning mechanism can only work when the centre of rotation is at the geometric centre of all the powered wheels. Currently it was in the centre of the front two wheels hence the entire back of the robot was getting dragged. Through more such question based triggers the participant is made to observe the bot and move the bot with her hand which help her in realising that moving and turning could also be possible with just the use of two diagonally opposite wheels and further as the non powered motor tyres were creating a drag she was able to overcome it by removing the rubber tyres as we have seen in Fig. 5.11 before. Here the reflection triggers let the participant playfully explore the behaviour of her bot with reference to her prior experience and based on the feedback of actions performed (moving the bot manually in two instances) she was able to determine her next steps towards the solutions.

In the following observation participant 4 is solving the problem of getting his bot from point A to point B. He has chosen and insisted on using an obstacle avoidance logic to reach from point A to point B to start with instead of doing the hard coded method first and then trying the obstacle avoidance logic as a part of autonomous navigation for the next problem. Here he has been using the proximity sensor to gauge the distance between the bot and the obstacle and once a threshold is reached the bot takes a left turn. In the previous run the bot had managed to reach point B but did not stop as he had not programmed that logic for it. Now as he tries to work with that it interferes with this obstacle avoidance logic. This is where this observation starts from.

- **DC11:** Reflections triggered with analogies or questions help learners consider failed attempts as opportunities to try new creative approaches and develop workarounds.

The following observation is of participant 2 when she was solving the challenge of moving the bot from point A to point B. This is also an extension into the observation 6.1 just at the beginning of the third part where the participant is trying to figure out how to get her bot to turn. This observation (11.1) shows how a mentor presents an analogy to the participant to make her reflect on the approach of making the bot turn. Further leads into the observation 10.1 where she is able to figure out a way of making the bot turn.

episode 11.1: *She coded one of the forward motors to turn forward and the other forward motor to turn in reverse expecting the robot to turn. But when she executes the commands she sees that the robot's wheels are spinning but the robot is not turning*. *The mentor asks "what is the turning mechanism that you are using" to which she replies "I am turning the front two wheels in opposite directions and that should turn the bot". Then the mentor asks "Is it different from the previous time when you were using the remote app to turn two wheels on one side forward and two wheels on the other side backward?". To which she replies "yes it's the same principle but I am using just two wheels in the front as I am not able to control all the four wheels at the same time using the code". The mentor looks at the bot and then looks at the participant and asks "Are you aware of how cars turn?" to which she replies "They have a steering wheel which turns the front two wheels making the cars turn." Then the mentor asks "Why do you think cars need to have a steering mechanism requiring the wheels to turn? Could we turn one wheel forward and the other wheel backward in a car and make it turn?". The participant takes a pause for a while, looks at the bot, tries to move it with her hands and then says "there can be a number of turning mechanisms and I guess cars have just a different kind of a turning mechanism." The mentor nods and says "Fair point", then the mentor questions "How do you plan to make the turn happen now?". She responds "Maybe by changing the steering mechanism to something else." The mentor looks at the bot, takes a pause and replies "Sure, but can you think of any idea where you use the current steering mechanism but the bot is able to turn?". The participant continues to look at the bot and says "The rear wheels are dragging so I am not sure". (continued in observation 10.1)*

Here we see that the mentor provides the analogy of a steering mechanism of a car and asks the participant to reflect on how steering the wheels makes the car turn and why do the cars not use this method. Though the participant responds by saying that they use different mechanisms we see based on the next responses this made her reflect and question her mechanism and its similarity to using all the wheels in a combination of forwards and reverse to turn the bot. As she later acknowledges that the rear wheels are dragging so she is not sure if she can use two wheels with this logic to turn the bot. Based on this realisation as we saw earlier in observation 10.1 she was able to narrow it down to the centre of rotation and later fix it by using opposite wheels.

Similarly P1 also initially used the same method to make the bot turn and the same analogy given by the mentor made her question her approach but she chose to change the design and replace the rear two wheels with a castor wheel. P3 has chosen to design a tricycle but when turning the front wheel it would not turn as the front arm was almost horizontal to the floor making the wheel flip. When the mentor got to know the motivation of her design was actually from an aeroplane he used that as an analogy to make her reflect on the angle of the arm of her bot which she then increased allowing the bot to turn. Hence based on how participants respond to analogy based triggers we could claim that the analogy based reflection allowed the learner to realise and accept the point of failure and she started thinking in terms of working on a workaround.

Even question based reflection allow participants to overcome when stuck e.g. for participant 1 in observation 7.1 where she was confused between solving the autonomous driving problem vs the problem of travelling from A to B the mentors intervention allowed her to solve the A to B problem first which in turn helped her in releasing how she could program the logic for autonomous driving. Apart from the analogy, mentor intervention helped participant 2 to look for different ways of controlling the bot remotely when she came across the remote control app for Lego and used it to control her bot manually before coding the path. The have been numerous such instances with all the participants like asking about the number of control statement P2 was aware of and it triggering her to reflect on the correct statement to used in a code block and questioning approach of P3 and P4 helped them reflect about the larger problem at hand and then overcoming it by changing their intermediate ideas of solutions.

- **DC12:** Prompts and checks from the mentor nudge learners to engage in playful exploration and perform actions on built artefacts to seek feedback.

episode 12.2: *The participant has been looking at both for a while and thinking what went wrong. That is when the mentor suggests "try to run it again and then try to see what is causing the problem". So she runs the bot a number of times and then picks the bot and tries to rotate the front wheel with her hands which would not rotate. She then says "Oh! The wheel is stuck" and continues to look at the bot again. Then the mentor then asks " what is not causing it to rotate?" The participant keeps looking at the bot for a while when the mentor says "try to run it and see what is going on, where is the problem exactly.". The participant runs the bot a few times and observes the behaviour of the various parts of the bot. She smiles then she runs the bot again and looks at it from a different angle. This time she says "o ok so the wheel is in a port with the cross and it is not letting the wheel move freely, maybe i'll have to use a new piece or wait" she then removes the wheel and fixes it in a hole above the cross which is circular and moves the wheel with her hands which now moves.*

Here we see the mentor nudges the participant to observe the bot's behaviour that made her take actions like running the bot again and trying to rotate the wheel with her hands. This action based feedback helps her realise that the problem is at the wheel. As she continues to observe she is also able to sort the challenge. We also saw in observation 4.2 a similar nudge from the mentor made the participant realise the reason behind the flimsiness and also made her look for a new piece that could help her overcome it. Many such instances were observed where the nudge from the mentors helped the participant in either focusing on particular aspect helping them to playfully explore that aspect makes them perform some physical action that helps them get feedback on the behaviour of the artefact they built which in this case was moving the front wheel of the bot using her hands to confirm that it was not free to rotate.

In another observation present below participant two has just figured out that she could use a phone app based remote to control her bot as a way of manually getting the bot to go from point A to point B. She has successfully connected the logo brick mounted on the bot to the phone and to the app and run a test code that conforms to a connection. She spent some time figuring out the function of the remote which has been presented later in observation 13.2. Now she has managed to create her own remote on the app and is testing the remote to control all the motors connected to the bot.

- **DC13:** Availability of just in time operational information helps learners remain engaged in playful exploration and seek meaningful and relevant assistance.

The following observation of participant 1 is when she was solving the challenge of moving the bot from point A to point B. She was attempting to turn the bot using both the front wheels like we observed in that case of P2. Unlike P2 when she was not able to figure out why the bot was not moving she chose to ditch the real wheels and just use two wheels. As she does that she has a conversation with the mentor as presented in the observation below.

episode 13.1: *She has removed the other side wheels of the bot. Now she looks at the bot and says "I am not sure if the robot will turn this way too", the mentor asks "What do you mean?". She points at the bot and says "Now the rear of the bot will drag so I will need something to keep it moving". Then the mentor then says "try something out, what is in your mind?" to which continues her search among the components. The mentor points her towards the Lego resource card that has all the components mentioned on it. She looks at the cards and then spots a red ball and asks "Is there a way I can attach it to the bot?". She continues the search for a while and then says "I guess I will have to change the design". Then the mentor then points towards the cards that have different types of wheels displayed. She picks the card and searches when she sees a castor wheel she says "this can work for an all direction motion and also support the brick while it moves". So she goes back to the resource and tries to locate the castor wheel and starts to figure out how to attach it to the other side of the bot.*

Here the participant chose to go ahead with a different design but had to figure out a way of ensuring the other side of the bot moves and does not drag. Mentor by pointing at the Lego resource card helped her search to find a piece that could help her make the bot stable. She then was able to locate a ball that gave her an idea that we may assume was the ball is free to move in all directions as she then asks if there was a way she could connect it to the bot. Here we see that her requests are now very specific and relevant to the current situation. She continues her search among the components. When she hints that the search seems to be in vain the mentor points towards a specific section of the reference card where she finds the caster wheel. Hence we may claim that with the help of the reference cards as a resource and timely intervention of the mentor the participant was able to continue her playful exploration and find a solution. One thing to observe is the time and how much the mentor chooses to intervene. The mentor initially just gave her the reference cards as she was searching from the resources and only when she had a very specific request regarding the wheel and was about to give up the mentor chose to point her to a relevant section instead of directly asking her to use the caster wheel.

In the next observation of participant 2 as she is trying to figure out how to control her bot manually and get it to move from point A to point B. As she is doing so she is told about the remote control app based on the phone by the mentor and the following observation continues from here.

episode 13.2: *She opens her phone and searches the play store for the "EV3 Commander app". She found it and installed it. As the app opens she explores it and then says "there are some remotes which I think are for some other specific robots". Mentor then says "Explore the options that are available". She continues to search and arrives at an option "build your own remote". She opens it and a message pops up saying "please connect to the EV3". She then says "Oh! I will have to connect with the brick first but how exactly is not mentioned". The mentor then says "Search on youtube you will get videos which you can follow" So she searches and finds a video. As she follows along she is able to make the connection successfully and continues to figure out the remote.*

Here the mentor tells the participant about the app and also directs her to search on youtube about getting the app installed and connected to the Lego brick which is just some operational information and does not require any critical or creative thought process. Easing such tasks helps the participants remain engaged in the creative process which is solving the problems. Here the participant is easily able to connect the remote but as we saw in observation 12.2 she still had to figure out how the joystick on the remote controls the individual motors. There the mentor nudges the participant to observe and reflect as that is a crucial part of reaching a solution.

Hence we could claim that if operational information is provided just in time it allows the learners remain engaged in playful exploration and based on the information the learners are able to refine their thought process and ask for meaningful and relevant assistance as we saw earlier when P1 discovered the ball and then asked about a mechanism to use it that ask some "something" to support the bot. Lots of similar instances were observed with all the participants like for P2 in the end of observation 9.1 when the mentor confirmed that the tyres could be removed from above the wheels it helped her get the bot moving.

- **DC14:** Reassurances from mentors help learners consider failed attempts as opportunities to try new creative approaches.

There are numerous instances where we see mentors reassuring the participants like the following observation which is a part of observation 9.1 where participant 2 is trying to code the bot to move forward or turn.

episode 14.1: *To move straight she initially codes the motors to move forward. The bot does not move forward. So she uses the code to move left for 5 rotations. She is surprised when the bot moves forward. She says "ok! This does not make sense" and looks at the mentor, to which the mentor says "but If you can control it this way just use this". She says "Ya i can" and starts to figure out an estimate on the number of rotations based on how far the bot travelled on the tile.*

In the above observation the bot behaves in a way that the participant was not expecting, which is moving straight when using the command to move it left. As the participant looks at the mentor, the mentor reassures her it was ok to continue to control it and eventually she was able to control the bot and also figured out why the behaviour was opposite to what the command was as the wheels were mounted in opposite directions as we saw in DC9. A lot of similar instances were observed when participants were confused among a number of options and asked the mentor to which the mentor asked them to pick one and go ahead to try it out. Like P4 was confused between the ultrasonic sensor and proximity sensor to measure the distances to calculate the volume of the room or which option of the reflection sensor to use to detect colour. The mentor in both the instances asked him to choose an option and try it and then he would be able to figure it out. This made him try the various and eventually figure out what he wanted to use. Similarly the mentor assured P3 to try various pieces which helped her find the right one to get the font wheel of her bot moving. In the case on P1 when she was confused between the 4 wheel vs the caster wheel approach the mentor reassured her that pick any one and you will figure it out. Here the reassurance seems to take the worry off the participants for an instance and they feel ok to try either of the approaches. A number of times the mentor reassured them that it was ok if their thought approach would not work. Maybe it will get them to know something that will help them eventually in taking a different creative approach.

A.2 DBR2

A.2.1 Findings for New and Modified Design Conjectures

- **DC 4`:** Access to resources displayed according to their functional characteristics supports learners to use materials in their own ways and perform actions on built artefacts to seek feedback.

  This conjecture is similar to DC4 for which we did find evidence but also released the additional challenges of an overhead of using a reference card requiring the learners to switch flow. In this study as well we have similar evidence for this conjecture where access to resources that are displayed helps participants use materials in their own ways and perform actions on built artefacts to seek feedback. The difference here was in the way the resources were arranged as per their functional characteristics. Hence the episodes we make here are on the ease of access to resources in comparison to the previous study based on participant perception with interview data where the participants were asked about the arrangement and also shown the reference card and asked if that would make any difference and what they would prefer. Additionally we also compared the time spent and their search trajectories for resource search. Following are the episodes from the interviews of the participants.

  Episodes: *Participant 1: [What do you think about the arrangement of the resources?] . . . The participant replies "They have been arranged as things I used to build then things I used to connect and wheels and gears parts and the motor and sensor parts. There are a lot of them so sometimes it takes time to find them but otherwise I know where to search when I need something. I think it is a good way of arranging things. . . . [When shown the card and asked about their preference towards arrangement] . . . . The participant replies "Well I think this arrangement (pointing at the trays) works, I never really had to struggle and as you had already told me about the layout I knew where to find what. Maybe the card can show me the variety of components but I do not think I will refer to it. (He picks the cards and looks at it for a moment) I think I have seen or used most of the components* *that have been shown here" The mentor then asks "What if the resources are arranged the way they are shown on the card?". The participant continues to stare at the card and then looks at the tray and asks "Are the resources on the card displayed as they are arranged currently?" to which the mentor replies "No they are arranged differently" then the participant continues to look at the tray and says "I prefer this (pointing at the trays) one. It's very easy to remember what is where and specific things I can find with some longer search which also gives me ideas so I am not sure if i will use the card that often."*

Participant 2: [What do you think about the arrangement of the resources?] . . .The participant said "It's fine, on the first day I took some time to search for components like the black pegs which I was searching on the bottom of this (pointing at the connecting components tray) tray but then once I know they are on the top of this try then I did not have to search. But ya a further categorization would make it more easy for small components". . . . [When shown the card and asked about their preference towards arrangement] . . . . The participant says "I think this way (pointing at the trays) is more easy as I know I will not look for links or joints from the red but I will just go there (pointing at the white tray) and look out for it. If you keep them like this (pointing at the card) then I have to keep memorising what is where or keep looking at the card. I think that would be a trouble. If you can categorise the current trays more that will definitely help"

Participant 3: [What do you think about the arrangement of the resources?] . . . The participant says "I did not know about any parts in the beginning so I was not sure what is what but as I was building with the instructions I got to know about the parts. Then I was able to search for them. But I knew if the part was a connecting part it would be in the white tray. I had a sense of where to search for what. . . . . [When shown the card and asked about their preference towards arrangement] . . . . The participant looks at the trays arranged and says "That way, the categorised parts" the mentor asks "Categorised in the sense?" to which he replies "The building parts and the connecting parts as I am able to find the parts very easily and the building is fast otherwise I will have to remember the places or keep looking at the cards"

Participant 4: [What do you think about the arrangement of the resources?] . . . The participant says "So first we go for the main parts which are the beams and then we *look for connecting parts to make connections so this is the kind of process that I was following. . . . . [When shown the card and asked about their preference towards arrangement] . . . . The participant looks at the trays arranged and says "The build with and the connect with arrangement, actually even this (looking at the cards) is fine but when you follow the process of first main building parts and then connecting parts this arrangement (looking at the trays arranged) is much easier to work with.*

Participant 5: [What do you think about the arrangement of the resources?] . . . The participant said there are so many so it was a bit confusing as there were a lot of things to choose from. If we keep only what we need it will be easier especially when we are building complex projects. . . . . [When shown the card and asked about their preference towards the arrangement] . . . .the participant says "Well I do not have a preference, I feel it should be arranged the way the person working wants it. The card actually helps me as it is easy to see the components and I guess there has been some thought put into the card as well if I was building with a manual but if I am building on my own maybe I will prefer them to be arranged in this (pointing at the trays arranged) manner.

Participant 6: [What do you think about the arrangement of the resources?] . . .the participant said "The parts were segregate so I was able to look and identify what would go with what like (he goes to the trays and picks a black beam and a peg) this beam will connect with the circular peg and (then goes and picks 5 pegs and says) this black is used to connect two but the blue is used to connect the three beams or frames and then the small blue is used when one side is cross and other is circle and the small reds are for two cross" to which the mentor asks "Did you know about the pieces already?" and the participant replies "No! I just looked at them and I got to know about the pieces". . . . . [When shown the card and asked about their preference towards the arrangement]. . . . The participant said "I think the pieces should be arranged, any way is fine, here (looking at the trays arranged) it is easy to search as I know building pieces are here and the connecting pieces are there."

Participant 7: [What do you think about the arrangement of the resources?] . . .The participant looks at the trays and says "This arrangement helped me a lot, initially on day one I knew where to search the pieces and with the progression and usage of the *pieces it became very easy to an extent that I did not have to think of where to find them". . . . . [When shown the card and asked about their preference towards the arrangement]. . . .She looked at the trays and said "I think for the problems you gave this arrangement is better maybe if we are building from the manual it may be easier to search for the piece as you are looking at the manual and the picture of the piece matches the one on the card but a for problems and making things on your own this (looking at the trays arranged) arrangement works very well"*

Participant 8: [What do you think about the arrangement of the resources?] . . . The participant says "As a new person who has never played with Lego this arrangement helped me, I mean it is easy to differentiate right, like if I have to connect two things I know there are a lot of options but all of them are in this (pointing at the white tray) tray so I can look and choose from these trays and decide what I want to use. I did not have to look at the other parts to see where the connector is. . . . . [When shown the card and asked about their preference towards the arrangement]. . . . participant gives a very surprised look and says "Obviously this! (looking at the trays arranged), rather I think they should be further classified in some sense like colour, shape etc".

To make a comparison on time spent, episodes of participants were chosen randomly and the time spent on accessing components from the tray and frequencies were calculated with manual observation. In addition to the time spent we also observed the trajectory of the search of components followed by the participants. Comparison among the participants of both the studies was made where they were trying to solve the same problem on the same day.

For the participants from study 1 the average time spent was between 7 - 10 seconds on an average when searching for pieces among which the search for a new piece took around 15 - 30 seconds whereas for known pieces took around 4 - 10 seconds based on the number of pieces picked in one go. The average number times they accessed the tray of day 1 and day 2 was between 75 - 100 but for day three it remained between around 30 - 40 times. In comparison with study two the average time spent was between 6 - 11 seconds on an average when searching for pieces among which the search for a new piece took around 10 - 23 seconds whereas for known pieces took around 2 - 10 seconds based on the number of pieces picked in one go. The average number of times they accessed the trays on day 1 was between 60 - 90, day 2 and day 3 was between 75 - 150. As for the trajectory of their search we found that once the participants of study 1 had decided the main piece which was a bit new, either by looking at tray or the reference card among the building pieces they would usually pick a standard connecting piece like the black peg or a blue peg and would only look for alternative pieces if the standard ones would not work. Whereas once the participants of study two had found their main piece from the building tray which was somewhat new they would look for the connecting piece and pick a number of options to try to connect using them. Once the connections and pieces become standard they would directly go to the relevant pace and pick the piece.

Based on the evidence from the episodes made during the interviews we may conclude that the arrangement based on function was helpful and also preferred among most of the participants. As the participants were allowed to access the manual, those who did refer to them felt the card based arrangement could be helpful in such a scenario whereas most of them agreed that a function based arrangement was preferable for open ended problems where one has to make solutions on their own. Especially as it aligned to their natural flow of finding a piece to build with and then connect with and allowed them to use the materials in a way they wanted to. Number of them also pointed out that the arrangements could vary as we saw in P5's episode who was seen arranging things on the table in his own way and then using them. A number of them additionally mentioned further classifying the component based on shape or form.

The times and frequencies do vary among the participants of the studies though not significant and the reasons behind them could be the change in the problem for the third day requiring them to build more and use more diverse components. The pattern of trajectory suggests that the classification based on functional affordances does lead to more experimentation as a number of option for the same functionality are available whereas such a thought process is not observed in the case where one has to find the building piece and the tendency remains to just go ahead and use the standard connecting piece. In the second case the search for alternate pieces is only seen when the standard pieces do not work or one is not able to realise their ideas with them.

Hence based on the participants perception presented in the episodes and the discussion above we can claim that the arrangement made as per the functional affordance not just allowed them but also aided them to use resources in their own way and also helped them to build their ideas into the physical in while engaged in the state of flow, so they could perform actions on the physical objects to seek feedback.

- **DC 16:** Providing demos of programming in the programming environment allows learners to engage in playful exploration.

A new addition to Tinkery 2.0 was demos, incorporated in its version 2 to ease the learners into programming so they could overcome the fear and let curiosity take over to explore the options available in the programming environment. The dome was given during the introduction to Tinkery. The demo consisted of showing the participants a code that draws / displays a graphic on the screen of the EV3 brick. This demo was also a way to ease into the requirement of challenge 3 in which the participants had to code the brick to display an expression on its screen which had to change based on the colour detected by the EV3 brick. Previously in DBR 1 we had one participant who did not have experience with programming and struggled with it hence we present evidence from participants who did not have prior exposure to programming as stated by them during the post interview, not prior to working with the session. Majors for all three of them was mechanical engineering for various private engineering colleges. The episodes below are from the post session interview talking about their experience about programming.

episodes: *Participant 2: [What was your experience with programming prior to this session ?] . . . . . The participant said "I have never done programming apart from my first year engineering course which I had to study to complete the coursework. I have never used programming for any other things. I knew that Lego has programming but I have never done any of those blocks and all". The mentor then asks "Did you know about loops and if else before?" to which he responds "Yes but I have never used them, we just had to wire the given programs to clear the exam". . .. . [How was your* *experience in programming Lego?]. . . . . . . .The participant responds "This is the first time I have done such kind of programming with blocks. I think this is an easy way. So the first program that you had shown, I first just tried to do that when I was doing the colour challenge and then I tried the sensor blocks to see how to use them and then used the serial monitor on the programming screen to understand how the sensor works. But then I realised that I had to keep the code running again. That is when I searched for the if else and forever blocks and understood so ya it was a nice experience."*

Participant 3: [What was your experience with programming prior to this session ?] . . . . . . .The participant said "I have never used or done programming before but I enjoyed this way of programming. Now I do realise that there are some aspects of the working of a car that I know very little about, especially the electronics. I have never done programming before". . . . . . [How was your experience in programming Lego?] . . . . .The participant said "I really enjoyed this way of programming, I did need some help like on the first day I was not able to figure out how to keep the code running. When I asked, you told me to check the control blocks. Then I tried the forever block and also read about the if and else blocks. I used them a lot, especially on the second and third day. Then also figuring out the value for rotations and degrees and the sensor I had to use the port view. But the control blocks helped a lot.". The mentor then asked "How did you figure out parallelisation, I mean running two sets of blocks at the same time?" to which the participant replied "I was exploring the event blocks when I saw the press button block and I used two of them to start front and back motors and it happened together"

Participant 6: [What was your experience with programming prior to this session ?] . . . . . . The participant mentioned "I had programming in first year but they taught us C/C++ and if we just learn the program it is enough to clear the exam. I have never done programming before. . . . . . . [How was your experience in programming Lego?] . . . .Here I tried the first program like the one you had shown. I wanted to try something different so instead of a display block I use the light colour block to make the led on the brick (EV3 brick) switch on in different colours. To detect the colour I found in events there was a block which I could use for colour so I just used that. Second day I just had two motors so I used the run block in the motors section. For the third day I was not able to run all the motors at the same time from the brick so I wrote a program to do that. Ya *programming helped but I did not need to use many blocks". Mentor asks "Why did you use the differential to power the two wheels and not two motors you could control them via programming ?" to which he replied "ya when I was building it I was not able to think of the programming part I realised that later when I was programming for the three motors. I also wanted to use the differential."*

episodes show that P2, P3 and P6 who claimed to not have experience in programming said they enjoyed working with the programming environment. Additionally what we see is they mention using the first program as their basis to start the exploration. By design the first program could be used as a part of the solution for challenge 3 hence this allowed the participants to have some basis to start from. Now when we compare the program written by all the participants for challenge 3 we see that there are variations which again arise based on the approach each participant took of the blocks they explored to solve the challenge.

When we continue to see the evolution of the way P2, P3 and P6 programmed we see that they were able to program their bots using a combination of control statements and event statements at times overcoming the need to control statements and implementing a parallelized approach through experimentation. This is evident in the case of P2 and P6 when trying to control more than two motors at the same time in programs for problem 2. When we compare this approach to participants who had exposure to programming P7 and P8, we see P6 used parallel statements right from the start but P2 and P3 had initially used control and even blocks for challenge 3. With experimentation they realised their later solutions with parallelisation to control all three motors at once which is fairly easy considering a scratch like environment. P7 and P8 on the other hand never used parallel blocks even if they knew it was possible in scratch. When later asked in the interview they said they knew they could do it with the control statement so they did not explore the other event blocks which are peculiar to Lego's version.

Figure A.5: Variations in participants code for solving challenge 3.

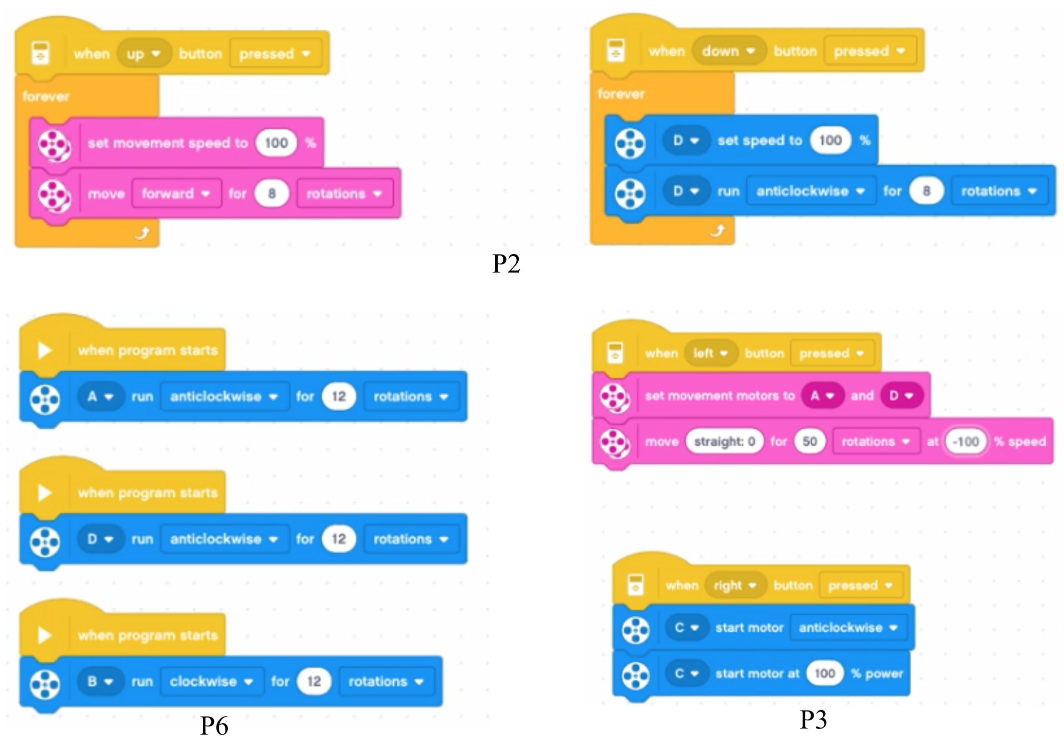


Figure A.6: Solutions for running three motors together for problem 2 with 2 parallel blocks.

Based on the episode made above and the discussion we may claim that giving demos to the participants did ease them into the programming environment and later we see they did explore a lot on their own and figured out various ways of programming their solutions.

- **DC 17:** Providing demos of using port view and motor controller allows learners to perform actions on built artefacts to seek feedback and troubleshoot iteratively.

In the previous studies we observed that the participants were not seen using the serial monitor and motor controller enough for quick trials hence in this version we explicitly gave them demos of how to view the intermediate states of motors and sensors using the serial monitor on the brick as well as the programming environment. As evidence we present scenarios from three participants who were trying to make their bot for problem two autonomous by using the proximity sensors as they were specifically using it to determine the values for their programs.

episodes: *Participant 2: He is trying to determine the value to code when the bot should stop. He has tried some values based on an estimate as he has told. As he is looking at the screen the mentor asks "Are you stuck somewhere?" to which he replies "I am trying to get the value for the sensor to make it stop at the obstacle". The mentor then asks "How far do you think it should stop?" to which the mentor looks at the bot and then picks it up and says "oh! I can measure it using the port view" and lift the bot and keep it on the floor to measure the distance at various stages. He then changes the program and then runs the bot. The bot stops very far from the obstacle. He then picks the bot again and takes keep it at three points and then says "I guess there is an interference as sometimes it's measuring the wall behind and not the object" then he take the bot very close to the obstacle and then looks at the value, comes back to the code and changes the value. He loads the code again and runs the bot. The bot travels straight and stops just before the obstacle.*

Participant 3: He has just coded the bot and is trying to decide the distance before the stop code should be executed. To do so he points the bot at things at various distances. As he does that he is observing the values the sensors report on the screen as the bot is connected to the Lego environment. He chooses the value of 10 cm and runs the bot. The bot does not stop and hits the obstacle. He picks the bot again then he covers the sensor with his hand which shows a value of 4 cm on the screen. So for the next trial he increases the value in the code and then runs the bot. The bot does not stop before the obstacle. He then looks at the code and then changes the condition to "<" from "=" and then runs the bot, which then stops before the obstacle.

Participant 5: He is trying to get his bot to detect obstacles and then stop but once the obstacle is removed he wants the bot to move again till it reaches the specified point B. When he tries the same code on a black box the bot stops but when he uses the translucent tray the bot does not stop. So he switches on the portview and then looks at the values the sensor reports while placing the tray in front. Based on the values he observes he changes the threshold value for the sensor and runs the bot again. Now the bot stops when the tray is placed in front. Then he tries it for the black box. The bot stops but at a greater distance than it was stopping before. The participant then says "I guess the transparency or the material has to do something with this variation."

Here we observe that the participants are using port view to get the real time values from the sensors. Most of these instances are when they are troubleshooting their code to get the correct values to make their bot stop well before the obstacle. With values seen live on port view the participants are able to uncover the challenges because of which their code is failing like in the case of P2 he got to know that the sensor at time is reading the wall behind the obstacle whereas P5 realises the sensor is giving different values when using different material. Similarly P3 is able to realise that there is a lower threshold to the sensor. Based on these episodes the participants modify the values in their code and are able to achieve the desired function from their bot as seen in Fig. A.7. There are similar instances when other participants were seen observing the number of rotations of the wheels or the degrees of rotation when trying to code the bot to go from A to B. Using those real time observations they are able to refine their code to solve the problem. When asked about it during the interview a number of them mentioned that the demo in the beginning and their first and second tasks is what gave them the idea of using the port view.

Hence based on the episode we may claim that the demo leading them to use the port view in challenge one and challenge two allows them to understand its affordance. Later they use these affordances to perform actions with their bot receiving feedback in terms of the real time values from the sensors. These real-time observations help them in reaching a solution for the problem at hand.

P2 measuring the distance P5 tyring the try as obstacle and observing sensor values.

P3 and his programming screen showing sensor values.

Figure A.7: Participants using port view to measure distances to program their bots.

A.2.2 Findings for Theoretical Conjectures

TC 3: Learners use materials in their own ways and express ideas and emotions with artefacts and actions to display a sense of pride and agency in their solutions and problem solving process.

&

TC 4: Learners take multiple approaches to solve problems, use materials in their own ways and develop workarounds to develop confidence in their problem solving process.

Episodes:

Participant 1: [When asked about his experience of working with Tinkery?] . . . . . . The participant said "The experience was very good. Working on this and making the whole model was very fun, I have not built anything before but, on the second day and today I have been able to build this bot. I am not able to believe this. I have just seen my friend who has built something and posted his picture and today I have been able to build it. I feel confident about using Lego and even making things. . . . . The mentor asks "why did you not just use the transfer case with the helical gear to use a parallel motion delivery motor and use a perpendicular low power motor for the differential?" to which the participant replied "Ya but that was not how I wanted to build the bot, I had thought to connect the motor directly to the bot so I wanted to go with my ideas. That is why I did not want to use the internet also, I wanted to think about my design and work on that". . . . . . . [When asked about any changes in his way of solving problems] . . . . . . The participant said " There might be a slight change, like I would be thinking about what you (mentor) would say and I would try to think in those terms. Apart from that my approach has usually been observation. I observe things to figure them out". The Mentor then asks "What when observation fails?" to which the participant replies "then I try to look for the weakest point and see how my imagination differs from what is happening. Like when my parents brought me RC cars I would want to open them and figure out how things work but if something was not as I had expected I would be more curious and look further trying things out. So that's all the changes I feel I will have in my process."

Participant 2: [When asked about his experience of working with Tinkery?] . . . . . . The participant said " The experience kept on getting better, First day I was completely blank and did not know much, the second day I was getting to know things which was more like brainstorming to get to know things and solve problems, the third day was the best as I was able to think and make the bot with my own ideas so now I am feeling confident and now I feel even if I keep thinking about the boy and the pieces I will be able to make it a lot better". . . . . . . [When asked about any changes in his way of solving problems] . . . . . . The participant said "The programming has definitely changed, I am able to use a lot of types of blocks and able to understand how different blocks can be used. Regarding the building I had used the manual initially but I feel the manual is too detailed and one can build those models in a simpler way.". . . . . . "I have realised that there are several ways to approach a problem. It helps my confidence as I can think of the same problems in a number of ways." . . . . . "If I am to work on a new kind of a kit I would first make something static to understand how the basic components connect and then try to build new things. That will give me some idea of what I want to build."

Participant 3: [When asked about his experience of working with Tinkery?] . . . . . . The participant said "The experience was awesome, I did realise I am lagging on certain basic aspects of a car's function and electronics. It was the first time I ever did programming". . . . . . . "Most of the time I was building and solving problems based on my own ideas. You were only helping when I had a problem and most of the time you just asked me questions and It gave me ideas.". . . . . . . [When asked about any changes in his way of solving problems] . . . . . . The participant said "I feel I can now think quicker," the participant was not able talk more and clarify about what he meant but through a lot of questions and given a specific problem of talking about a dog feeding machine he initially talked about multiple ways of building it and a number of additional ways of achieving the ideas. He kept mentioning "I am confident I can figure something out".

Participant 4: [When asked about his experience of working with Tinkery?] . . . . . . The participant said "The knowledge was increasing day by day and the experience was amazing. The first day was about visualising the problem, the second day for me was more about building, the third day was a bit challenging. As I had to think a lot but was able to use a lot of my ideas. On day two the idea that I took was from the manual. A number of times I did have an idea of what I wanted to do but when you were talking to me it clicked on how I could do it.". . . . . . . [When *asked about any changes in his way of solving problems] . . . . . . The participant said "The change that I see is in the thought process aaaa….. things we know might not be so straightforward when we try to implement it.". The mentor (who is also the interviewer) then asks "ok! So that is on the conceptual level. Do you see a change in the way you usually approach a problem?" to which the P4 replies, "yes now there seems to be a structure to it, so now like today (day3) I started to think and visualise the solution and then build it along with some trial errors to see if things are working the way I anticipated they should and eventually figure out the challenges. Now it seems like an ongoing process."*

Participant 5: [When asked about his experience of working with Tinkery?] . . . . . . The participant said "Different tasks gave me an option to try different ideas and also use different ways like planning and also trial and error type of methods and also I do not have to complicate things and there could be simple ways to do it. I really enjoyed that I had the freedom of doing the things I wanted to do, and using my ideas and you (mentor) did not intervene unless I was really stuck or I asked for it. So now I feel more confident about having solved these problems this way. I thought of doing them". . . . . . . [When asked about any changes in his way of solving problems] . . . . . . The participant said, " yes there has been a change. Now I feel that there are a number of possibilities and I think I will wait and think of those and maybe pick one and then figure out how to process. Earlier It was more of any idea I got had to be the only way of solving a problem. Another major change was trial and error, I never used to do that a lot but these days I did a lot of it". The mentor then asks "Talk more about the trial and error, is it random like try this and then that till something works out.?" to which the participant responded "No no! It is more like if I have a path in mind and there are a number of options to get there then I will pick one that sounds logical to me and I will try that. Based on what happens now I can think of which next option should I try or do I need an entirely new path. It basically helps me channelize my thoughts"

Participant 6: [When asked about his experience of working with Tinkery?] . . . . . . The participant said "I had a lot of fun, I really enjoyed it. I had a clear idea of how I wanted to use the rack pinion for turning and differential and I was able to use it. Now I feel confident that I will be able to figure out how components". . . . . . . [When asked about any changes in his way of solving problems] . . . . . . The participant said " Most of the time I was doing what I wanted to unless I got stuck. And confidence is another thing as I also realised there are a number of ways *of solving problems and we should give a thought about the idea we want to start with. One way could be to sketch it or lay the components out to visualise if that will work. It helps to get a better understanding about our ideas and if they will work or not. It's like testing the idea without actually testing it".*

Participant 7: [When asked about his experience of working with Tinkery?] . . . . . . The participant said " The building part was challenging for me initially, the programming part I was very comfortable with even on day two I was not sure about how to build so I had referred to the manual. Through day two with the building and getting to know about the pieces on day three I was able to think of solving with my own ideas. Rather I was able to think of my ideas using the kit components hence I can say there has been a substantial change in my confidence". . . . . . . [When asked about any changes in his way of solving problems] . . . . . . The participant said " One change I do see is in the loss of inhibition of am I doing right or not, Now I am more comfortable with the try it and see approach. This makes me more comfortable about trying things out.".

Participant 8: The video file snippets of these sections of the interview of P8 were found to be corrupt hence the data is not available. Based on the interview logs we can say that she reported a sense of confidence on using ideas that include mechanics. Additionally it was noted that she had mentioned about the use of focused trial and error.

Appendix B

Sample Narratives

B.1 Sample Narrative 1 DBR1

In this section the participant has been asked to create a robot using four wheels that can go forward or backward. Today's problem has been expanded by asking the participant to make a bot that can travel from a given point A to another given point B. The room in which the participant is to perform this task is layered with square tiles and the participant could use the edges of the tiles as a way to reach from point A to point B avoiding all the obstacles.

For now the participant need not follow a given path but can use any edges of the floor tiles. The participant is also free to choose any design or type for the robot which could vary between a four wheel design to 3 will design or what they wish. The participant decides to start with the model she had built the previous day. It was a four wheel design. The model was primarily built using frames. The mentor had clarified that she was free to choose the design that she wanted to work with.

She started with the previous model, the four wheel version starting by removing the connecting bricks. She then removed all the wires and re-attached the rear wheels to the frame using blocks and pegs. Then she attached the bricks to the frame. To stabilise the bricks on the frame she picked the four types of pegs. These pegs were all arranged as per the Lego kit and the pegs were kept all together. This double frame black pegs. As she examined them she kept the short double frame black connectors to her left hand then picked the red connectors which she compared visually in terms of the length and the head cross-section. She realised that that was not the peg she wanted then she took the brown peg again.
She tried to attach the connector to the brick and frame but was not able to so she gave up on the idea to make the base firm. Then she moved to connecting the wires to the motor and the brick

and program and see if the current structure can sustain the motion. So she connects the brick with the robot and starts with the programming of the robot. She says her plan is to use the buttons on the board as a remote control to connect and control the brick movement. (C10,11) She starts programming the press action of the buttons to control the front, the side and the back motors of the robot by controlling the motor speed and direction. When she tests the program by loading it on the brick she realises that it did not work. When she looks at the screen on the execution she realises that she will need to keep a loop statement to ensure that the button press is a key executed whenever the button is pressed. She then searches the Internet for an implementation of a loop. The mentor asks how she wants the loop to behave. She says she wants the action to happen every time the button is pressed so she needs a loop for it. Initially she chose a repeat until function for the left button when it was pressed which did not seem to work. The mentor then asks of the different kinds of loops she is aware of? To which she says the challenge here is that the blocks will have to be in a continuous loop to work. In the current state the blocks get executed as soon as the program runs and does not look for an input after the first execution. She continues her search now for a type of while loop and is able to find it out. With the while loop true now she is able to control the motors. Now as the blocks get executed sequentially she realises she is not able to turn all the Motors at the same time and now she is searching for various other blocks that you could use to drive the motors together. She discovers a block labelled as motor movement. The way this block requires input suggests to her that this block could be used to turn two Motors simultaneously. To test it out she uses the block and applies it to the one module which has the front wheels and uses the front button function to test it out. She realises that In the given set up the wheels only move for the number of rotations that have been coded whereas she would need the wheels to keep running till the button is pressed or she would have to keep pressing the button again and again to make the robot move forward. Here the mentor intervenes and asks How are you dealing with the problem of sequential execution of the commands? She replies she has figured out the use of these movement blocks which allow her to control two Motors at a time but now she has discovered a new problem. She says that I want the bot to move as long as the buttons remain pressed and not press them again and again. Then the mentor reiterates the problem that she is trying to solve by asking “Is it that you have to get it done via remote in a specific way on the brick or you just have to get the bot from point A to point B. She replies the way she can get the brick from point A to point B is by controlling it somehow. The mentor acknowledges and mentions that this remote is just one way of getting the bot to go from point A to point B. The mentor then mentioned that she is still free to choose a way in which she would not even require a remote.

She starts a search on Google looking for remote controlled EV3 robots where she is able to find a solution where one could control the EV3 robot using an EV3 application on the phone. This would require her to connect the brick with the EV3 using Bluetooth. She immediately opens and downloads the application from Google play store and searches for The video which shows the way of connecting the application with the EV3 brick and using it as a remote control. Initially she is not able to figure out the way of connecting the app to the break but through a search of two or three videos she is finally able to establish a connection And transfer a file to the EV3 break from the application which was not happening earlier and now that she has got the file transferred she is able to execute the file on the break and when she clicks the forward and reverse button on the app she see the motors move but the response was not as she would have expected. The motors that were turning but not the ones she wanted to and not in the direction she wanted to so now she had to figure out a way in which she could turn the motors in a given direction. The mentor realised that she had not explored the app completely to realise there are more options but the mentor abstains from prompting. She says that even now she could only control two motors at a time. So she decided to remove two Motors and continue building with just two motors for now. She also had to figure out a different way to make the robot stable so she removed the middle frame and kept the side frame with just two motors and mounted the brick on top. Seeing this the mentor asks if she had changed her plans of making the robot. She said yes that she has removed the other side wheels of the robot. But she’s not sure if the robot will turn this way. Then the mentor points towards a caster that can allow a 360° motion. The learner says yes this can work for an all direction motion and also support the brick while it moves. But then she mentioned that she had seen a video where they were able to make the board go forward and backward all with the application. Is that the mentor responds and says Why don’t you look for all the options that are available on the application. So she goes back to the application and tries to search for different options that are available and then she finds an option to control a two wheeled bot and she tries to use that option. As even that does not work as she intended she tries to search more and that is when she is able to find an option which allows her to configure a remote according to her own choice. In the configuration window she is able to use two joysticks that can turn to Motors forward or backward. And eventually she figures out she could use such joysticks to move the robots forward backward and even control two wins by moving them in opposite directions to control the robot.

That is when she goes back to building the robot with all the four wheels for Motors as it already was. Then she connects the robot motors to the brick and then tries to run a small trial of moving the bot. As she moves the joysticks she realises that the back wheels are moving clockwise when she moves the joystick forward and they move in opposite directions in an alternating manner when she moves the joystick right and left. Similarly for front wheels. Currently the back wheels were connected to port A and D and front wheels to B and C. The challenge was to get both wheels on the left to move clockwise and right ones anti so she could make it turn. Upon asking her the mentor gets to realise she is confused as she tries to figure out and is just trying random combinations of ports and joysticks. The mentor asks her to try and see how she can do it by observing how the wheels are turning with what kind of movement on the joystick. She then figures out that when she moves the left joystick forward the left wheels turn in opposite directions so she connects the right rear wheel to the port on which the left rear wheel is connected and similarly connects the right wheels. So now when she moves the joy sticks to the right the bot moves forward and when she moves both forward it turns left. So just use that to figure out a way to move the bot from A to B. When the mentor later asks why it behaves this way she says I am not sure I just realised a way to move the bot forward and make it turn.

B.2 Sample Narrative 2 DBR1

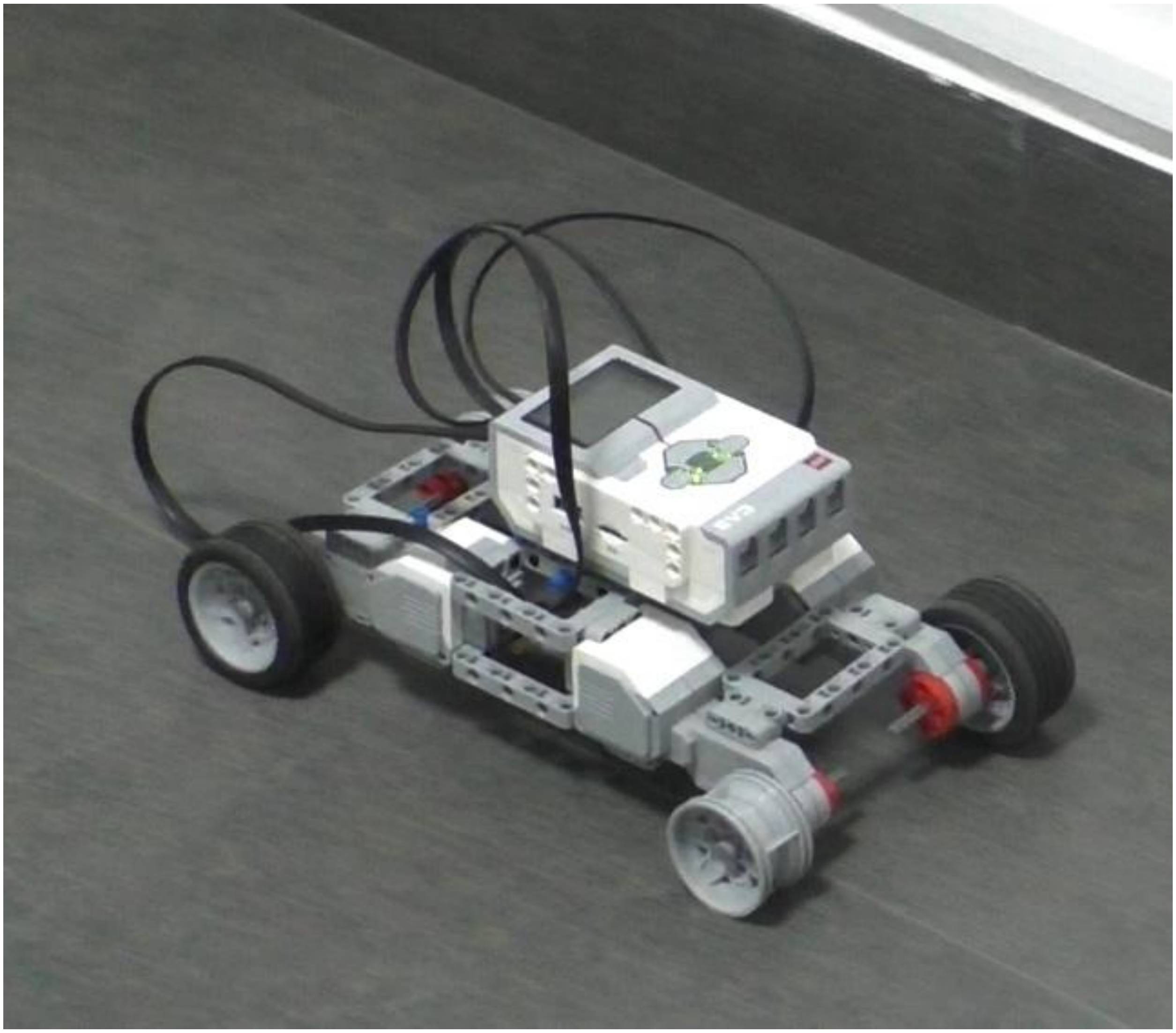
So the participant has been told that the Robot should go from point A to point B without manually controlling the bot. So she starts thinking about different ways the robot would be made. Her initial idea is to build a robot which can detect and avoid obstacles which can be seen based on her search sheet as on google and looks at research papers talking about using ultrasonic sensors to avoid obstacles. Then she tries to figure out a way of using ultrasonic sensors in Lego mind storm to make an obstacle avoidance robot. The mentor interrupts and asks her about her approach to solve the problem. So she tells about her idea of detecting obstacles using ultrasonic sensors but she's not sure how the robot should react when it detects an obstacle. So the mentor asks let's look at what the problem is. The mentor says that the robot is supposed to go from point A to point B and we know where the points are. So do we really need an obstacle avoidance system for the robot to go from point A to point B? The participant responds, "If the robot knows where the obstacles are and knows how to go from point A to point B then it can be done". The mentor says okay then let's try to find a way in which the robot can already know how to get from point A to point B.

The participant goes back to the coding window and tries to code the Motors to see if it can run forward autonomously. To do that the participant chooses the run block and sequentially adds four blocks for each motor to run forward for one rotation. As soon as the participant executes the program She realises that coding the block sequentially moves the motor one at a time and not all the motors move forward together. That is when he starts looking at what blocks are available where she finds the movement block. She looks at the different blocks that are available in the moment lock and chooses the move block. Then she tries to browse for Solutions that will allow her to move the motors at a time with the moment block. Based on research she realises she has to use the set movement motor block before the move block. So she uses those two blocks and then tries to move the body forward by coding to simultaneous code that would run to different motors in the straight direction for one rotation each. She experiments with different ports to see which code block should be coded for which motor port but is not able to get the bot to move forward.

She still tries to search for a way in which he will be able to control all four motors and get them moving forward. Even though she has selected the direction forward for both the blocks, two wheels tend to turn in reverse and two wheels tend to turn forward. She asked the mentor if both the commands were actually getting executed at the same time which she feels is not happening. The mentor replies by saying that if you select both the blocks or just click on run all the blocks with the control block run when the program begins will get executed. Then the mentor asks if she is able to move the robot in the front direction. The participant shows her code and says she has coded for all motors to go in the forward direction. The mentor then looks at the robot and points to the rear two wheels. She then exclaims two of the wheels are mounted as reverse whereas two are mounted forward. Then she says that to move all of them in the forward direction we would have to set the movement direction in reverse for two of the motors and forward for two of the motors. But for some reason even with coding to start with the program blocks she was only able to control two motors at the same time. So she decided that she would only control Motors and try to move the brick. By controlling two Motors in the front she was able to move the robot forward. Now she had to figure out how to turn the robot. So she coded one of the forward Motors to turn forward and the other forward motor to turn in reverse expecting that the robot Would turn. But when she executes the commands she sees that the robot is taking a lot of time and effort to turn and that it would be very very slow. So now the mentor asks what is the turning mechanism that you are using to which she replies I am turning the front two wheels in opposite directions and the robot Should turn. Then the mentor asks how it is different or is it different from the previous time when she was using the Motors and turning two wheels on one side forward and two wheels on the other Side backward. The mentor also says why do you think cars need to have a steering mechanism and not just one wheel forward and the other wheel backward. The participant says there can be a number of turning mechanisms and the cars have just a different kind of a turning mechanism. The mentor asks okay let's look at how the position of the components of the robot changes when we turn just the front to Motors opposite or we use all four motors in opposite directions. The participant replies that when moving just the front wheels are causing the rear two wheels to drift and slide to make the robot turn. To which the mentor responds, can you think of a way so that the turning axis is not between the front to Motors but at the centre of the robot. The participant responds by saying maybe by changing the steering mechanism so the mentor replies yes but can you think of An idea where you use the same steering mechanism but the bot is able to turn with the turning axis centring at the centre of the bot. She looks at the bot for some time and then asks if she is able to control all the four motors at the same time. I might be able to do that. The mentor asks if she can do it with the 2 motors too to which she replies maybe if she uses the two diagonal wheels she will be able to turn and also move.

She then codes the diagonal two wheels to run the bot. She uses the set movement block setting the motors on ports B and D as movement motors. To move straight she initially codes the motors to move forward. The bot is not able to move forward.

So she uses the code to move left for 5 rotations and to her surprise the bot moves forward. Though this does not make any sense she figures out an estimate on the number of rotations based on her first test and how far the bot travelled on the tile. So now the bot is able to move forward but now she is confused about turning the bot so she adds the move forward block back and she observes that the wheels are moving in opposite directions when she lifts the bot up but they just seem to give a jerk and not move when on the ground. Then she says i think i will have to redesign the entire bot as two wheels. The mentor interrupts and asks why do you think this is happening? She says i think the two wheel idea won’t work to which the mentor asks why is she saying that? She says she feels the wheels are not free to move as drag wheels. To which the mentor says Is there a way where you could test this? She replies I'll have to remove the motors I guess to which the mentor replies that the rubber tyres of the wheels are removable. So she removes the rubber from one of the tyres as she wants to use both the back tyres to move forward. The bot moves forward perfectly but as it tries to turn one of the rear wheels still shows some resistance. So she decides to remove the rubber from one of the rear wheels also and then test the bot.



Controlling the diagonal two motors which allows the bot to move forward and turn. Now she codes the movement as follows as an estimate and runs the bot.

Based on the run she realises the turn executed was not substantial hence she changes the forward value estimate of how many rotations she will need to make the turn.

What was interesting to observe was that the bot has the forward and backward motors mounted in opposite directions so when the move forward command is executed the front and backward wheels both turn clockwise with reference to the motors but they are moving in opposite directions on the bot. Hence the command to make forward movement is actually turning the bot and vice versa. When the participant was asked about why this is happening she replied that due to the way the wheels were mounted it was moving the wheels in the opposite direction using the forward motion block so she chose to just use the turn block to move forward. She said she figured out the turn value when kept at 100 was making the bot move forward so she chose to go with that instead of reorienting the wheels. This shows the participant is not just aware of the affordances of the motors and how the programming blocks control them but is able to use the block as per her design requirement and not how they were intended to be used. The participant has not just understood the affordance but has tweaked them according to her requirement. (Theoretical conjecture evidence)

Appendix C

C.1 Tinker Bot

It is understood that a mentor can address these challenges by scaffolding and aiding reflection. We believe a mentor supported by a semi-automated agent can have a tremendous impact on familiarisation with the robotics kits. We explored an idea of a chatbot based Semi-Automated agent as a companion with tinkering kits. After analysing interactions between a mentor and a participant in the robotics workshops we classified the types of such interactions. This has been used to develop a scaffolding logic to automate certain routines of interactions using the chatbot. Such a chatbot can act as a scaffolding agent as well as companion for journaling and could also open the possibilities to remote or virtual mentoring.

To aid reflection and overcome challenges of getting stuck while working with Robotics Kit we designed a chatbot, "TinkerBot". Chatbots are increasingly being used for automating conversations. In addition to automated conversations, chatbots can send scheduled messages, and can be useful for sharing files and documents and other resources. They are also equipped with interactive messages which can be leveraged for structured conversations, they involve forms which can be used for collecting user feedback or creating a log journal. They can store and retrieve data from databases and help in monitoring user activity.

The scaffolding logic governs the automated and semi automated prompts and triggers given on the basis of the progression of the participant in a given challenge from their logs or by time-based events or based on participant's activity on the app or prompts explicitly sent by the mentor. Several routines of mentor participant interactions were identified from a tinkering workshop done in a physical setting. Based on the observations and classification of the interactions, certain routines were selected to automate them in the form of conversations. The Scaffolding Logic is designed as a decision tree based on the observed routines. When an event is raised, in form of a message from participant or mentor or internally by the activity monitor, the scaffolding logic takes this event and participant state and as input, computes the response based on the scaffolding logic as seen in Fig. 1 and makes updates if any. The required resources or information is then pulled from the data store to structure the output which could be the next message.

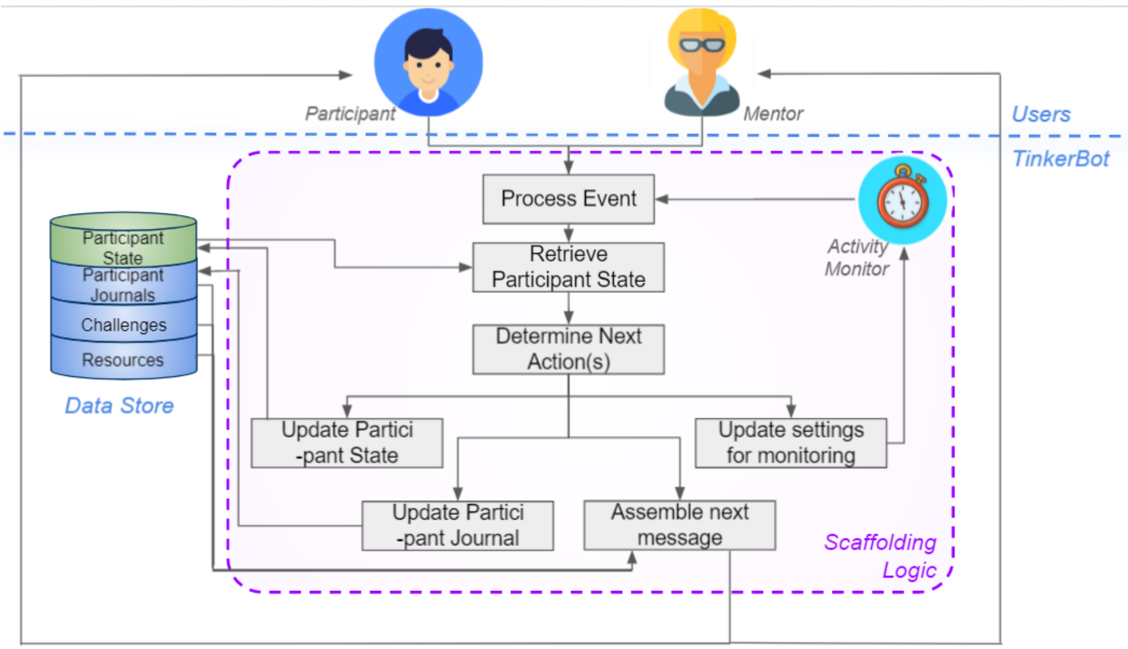
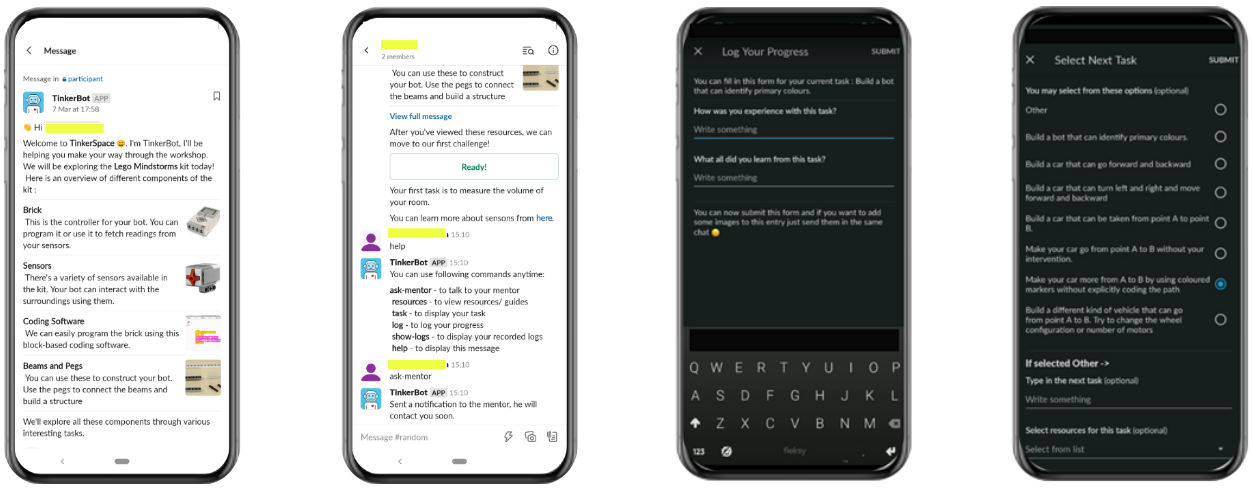


Figure C.1: Scaffolding logic and it's interaction with Users, Data Store and Monitoring App

In the current state of development,we have coded several routines into TinkerBot, few of them are shown in Fig. 2, TinkerBot can manage complete flow of a challenge completion. When a new participant is registered, TinkerBot sends an interactive message as shown in Fig. 2(a), it introduces all the components of the LEGO Mindstorm Kit. The messages are written with emojis and using the pronoun "we" to make it seem like a friendly companion. Fig. 2(b) shows the routine after generic introduction: TinkerBot waits for the participant to go through the shared resources, after which the participant would hit "Ready", implying they are ready for their first challenge and then the bot would send the problem statement along with the other detailed resources required to solve the problem. We have added a few intuitive commands for both participant and mentor. Fig. 8.3 (b) shows the commands that can be used by a participant, like "help" and "ask-mentor". "Help" can be used to display the list of commands and when a participant sends the "ask-mentor" command, the mentor is notified through a different channel on Slack so that he / she can join and help the participant. Few commands like "resources" ,"task" are common between mentor and participant and mentor also has other advanced commands. Fig.

8.3(c) shows the form to add a log to the participant's journal; if the participant wants, they can also add pictures to it by attaching files in the chat. Fig. 8.3(d) shows another form, which is for the mentor to select the next task(challenge) for the participant. He / She can select from the list or create a custom challenge, depending on the participant's progress.



(a) (b) (c) (d)

Figure C.2: (a) Interactive introductory message received by the participant. (b) Participant can discuss with mentor on same platform. (c) Forms to create a logging journal. (d) Mentor can select next challenge from the list or can create a custom challenge

In this exploration we attempted to understand the process of solving a challenge and did an analysis of mentor-participant interaction, we identified events which initiate a conversation between mentor and participant and we classified different types of prompts given by the mentor. These states, events and prompts together helped us to develop routines of conversations which were coded into the chatbot in form of decision trees. We plan to conduct studies in future, using the proposed chatbot as the scaffolding agent and explore further possibilities. While a mentor is irreplaceable, developing a hybrid model can prove to be very efficient as a mentor's presence is limited. Chatbots conversational nature can allow it to act as a companion which is limited with a mentor. Through TinkerBot, a single mentor can manage multiple participants, especially helping the mentor off load various tasks.

C.2 Tink-Mate

This exploration was carried out to address the challenges of seamless information exchange for which we propose to design a tinkering companion for engineering design kits namely Tink-Mate, a mobile phone-based platform which provides information and triggers as and when required via two seamless mediums of interaction as shown in Fig. 8.4. Firstly it will use a tiny robot as a physical pedagogical agent (PPA) that sits on a work table allowing the user and Tink-Mate to interact using speech and image recognition capabilities vocally. E.g., instruction from the PPA saying “Start simple and start making?” to encourage constructing with the first simple idea. It would also provide behavioural triggers like expressions and human-like body motion as seen in Fig. 8.5. Secondly, Tink-Mate's phone-based augmented reality (AR) feature would augment information about the kit's components to ease exploration and experimentation with them. E.g., Information about use and configuration of a sensor like its pinout diagram, voltages, and frequencies provided by augmenting it over and around the device. The ideas of Tink-Mate parallels Jarvis, the fictional AI assistant and companion of Tony Stark, a character from Marvel cinematic universe.

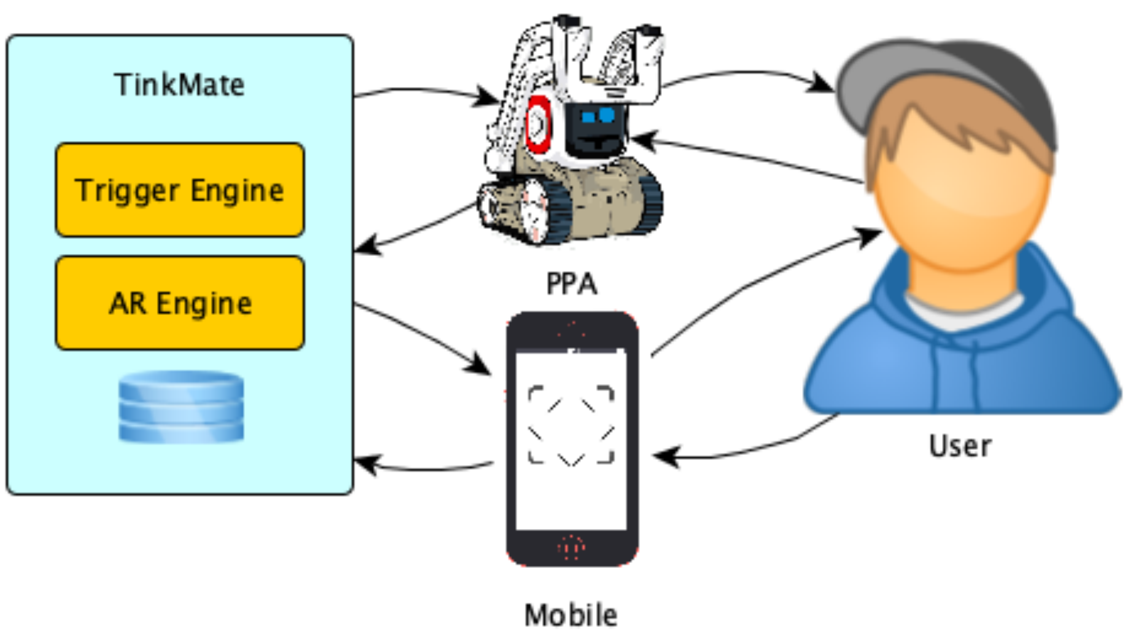


Figure C.3: Overview of seamless interactions between Tink mate and the user

Literature has reported that introduction of interactive pedagogical agents who communicate with students via voice and animated behaviour show evidence of meaningful learning as the students had remembered more and transferred what they had learned to solve new problems (Karim et al., 2015). A robot could add to the advantage of a teaching agent by being present in the physical space and allowing seamless interaction via speech, visuals, and behaviour. Robots are being used in education in various roles (Cheng et al., 2017). Augmenting information on the physical object reduces the overhead of interpreting data from multiple sources and associating the object with the acquired information (Ibáñez & Delgado-Kloos, 2018). Many applications in education have used Augmented Reality to augment digital information on physical objects(Ching et al., 2018). Though AR and PPA will enable Tink-Mate to provide information seamlessly via speech and visuals, we still need to identify features that would enable Tink-Mate to do so. We conducted a contextual inquiry to identify features for a seamless interactive tinkering companion that would support users with information essential for engineering design problems without searching for it extensively.

Figure C.4: Features of a physical pedagogical agent (COZMO) that would enable seamless interaction between TinkMate and the user.

The aim was to develop an initial proof of concept for Tink-Mate for which we considered getting an off the shelf educational robot. We surveyed all the available candidate options from different manufacturers in a similar price range based on the features discussed above and small form factor to ensure its subtle presence in the working environment with freedom to obtain the data from the robot and program its behaviour using an API. COZMO by Anki technologies as it satisfies all the above mentioned criteria. Even through further exploration we realised that the extent of time and behavioural research exploration would be required to do justice to the affordances of such a robot hence we choose to keep it as an additional exploration as an option of being able to use it as an expressive learning agent.

Appendix D

D.1 Guiding Questions for semi structured interviews

Pre Session :-

- Tell me about yourself ?
    - Educational Background
        - subjects etc
    - Experience with Robotics
        - arduino etc
    - Other Extra curricular interests
    - Probe for any off curricular tinkering
- Hypothetical Situation of giving a kit which has parts and manual
    - How have you worked with such kit in the past.
    - How will you explore a new kit ?
- Hypothetical situation of making a pet feeding machine ?

Introduction :-

Lego Construction block types - To Build, To Join, To move, Other

Lego Motors - Motor Controller

Lego Sensors - Serial Monitor Motor controller

Lego Brick - Programming Environment

Post Session:

How was your experience ?

What did you do today ?

What did you learn from it ?

How and where do you think you could use this ?

Probe more in case the response is general

Post Workshop -

Tell me about your experience in the workshop ?

Did you use the semi-built scaffolds ? Why and how ?

Did you observe the distribution of components ? Did you use it ? Did it help ? How Did it help ?

Did the mentor intervention help ? and not help or was intrusive ? DDid it influence your problem solving process ?

Do you feel there has been any change in the way you would approach a problem ?

If you were given a kit like Lego how would you approach it ?

If you were given a kit very different from lego how would you approach it ?

Would there be a difference in your approach when getting to know about a new kit?

Why

What do you think would drive you to get to know about a new kit ?

Hypothetical problem of a fully autonomous maze solving robot

How is your approach to the Autonomous maize problem different now as compared to before the workshop ?

X - When given a new problem how do you think you would approach a new problem given some resources you have to solve it ?

• Explore Solve Evolve - Questions from cycle one to which additional confirmation will be useful

Appendix E

Addendum

Added as per the instructions from reviewer 2 in responses to his comments.

Lack of critical analysis: although there is discussion on research gaps, I feel that was somewhat informally presented. The limitations are too vaguely mentioned, mostly using generic terms. It is desirable to be a little more specific on the research gaps with respect to the work you have done.	Thank you for the comment. The gaps are mentioned in para 6 of section 1.1 and section 2.5. They specifically target the practices in traditional ways of conducting engineering labs (with supporting literature), as mentioned in para 6 of section 1.1, and the activities associated with an engineering design that claims to be associated with tinkering. It has been reported that most research on tinkering focuses on learning using tinkering and not problem-solving with tinkering or tinkering as a practice in itself.
The stated aim of the research is to propose a learning environment that supports tinkering in the context of engineering design problems. However, a very specific design problem is chosen to represent the problem domain. It is not clear how that choice is made. It requires some sort of characterization of the problem domain and demonstrating that the chosen problem satisfies those characteristics. In the absence of that, it appears to be a random choice without much scope for generalizability.	Thank you for the comment. The choice of the design problem has been made after considering the context of engineering design, the resources that have been chosen, and the participants' exposure to engineering design. To do so, a number of engineering design problems were collected, solved and evaluated in terms of variability of materials and complexity in terms of the number of design variables that will be required to manage and manipulate to arrive at a solution. The researchers solved the problems in a number of variations. The problem design was evaluated in DBR1 and redesigned to ensure the challenges were not observed. This process with specific problems of choice has been discussed in section 4.3.3, bullet one and section 5.2.1 in detail. The changes and its reason for problem 2 in DBR2 have been discussed in section 6.2.
The quality of English can be improved. Sometimes, grammatically incomplete sentences appear in the text. There is also a tendency to use long and poor quality sentences. Shorter and concise sentences would have been better, I feel. At many places, there are repetitions and missing punctuation marks as well.	Thank you for highlighting the concern. The thesis is being checked for structure and grammar.

Sec 1.1 – too much detailed discussion on tinkering, which I believe doesn't merit such verbose explanations. Could have been shortened. Also, the example, in my opinion, doesn't really add anything to the understanding of tinkering and can be omitted.	Thank you for the comment. Tinkering is a very variedly understood topic and has been associated with a number of terms like jugaad. The research progress committee also pointed out the need to address this variability, requiring an extensive discussion. The example has been used to bring out the differentiation between jugaad and tinkering, the differentiation of the process. The example helps to highlight the difference.
Pg 4, last para, 1st sentence – the statement seems strong. Different kits may have been designed keeping in mind different goals. I don't think there should be any single "best practice" to cater to all situations and goals.	Thank you for the comment. Different kits can be built for various contexts, learning outcomes, etc. I do not suggest having one single best kit. The concern that is being highlighted is if it is a tinkering kit or uses the word tinkering, it should at least subscribe to the requirements of tinkerablity and scaffold the tinkering ability of the learner irrespective of the objective the kit is trying to achieve. The emphasis is on designing the kit and the activities in such a way that they encourage or at the least support tinkering.
Sec 1.3 – RQ1 mentions "features & activities". RQ2 seems to refer to the "process", which again refers to "activities". Aren't these two research questions similar?	Thank you for the comment. The RQ1 focuses on the "features and activities" of the learning environment. This RQ evaluates if the learning environment's features support the mediating processes. At the same time, the RQ2 looks at the mediating processes of tinkering and evaluates if the processes result in expected outcomes from a tinkering-based activity taken from the learning dimensions framework. Conjecture maps have been used to evaluate where RQ1 is answered using the design conjectures that evaluate the features against the mediating processes they should support. RQ2 is answered using the theoretical conjectures where mediating processes have resulted in the expected outcomes. Hence these questions are being used to answer two different parts of the objective of designing a learning environment for nurturing tinkering in the context of problem-solving in engineering design.
Sec 2.1.5 – seems to appear suddenly.	Thank you for the comment. The reason for adding bricolage and jugaad is that they are more frequently and commonly used in tinkering-like activities. One often tries to understand tinkering through those terms. It is important to clarify the differences, like the evolution of solution, which is not considered in Jaggad but is important for tinkering.

2. Sec 2.1.6 – are you proposing a new definition of tinkering? If yes, the difference with the current definition is not very clear. The difference should be highlighted in a better way.	Thank you for the comment. All the various definitions of tinkering have been presented in the opening of section 2.1. Given the variations in the definitions, it took time to understand tinkering; hence in the entire literature review, we discuss tinkering based on the nature of activities, goals, processes and orientation. Hence in 2.1.6, it is emphasised that one has to look at tinkering through all these four aspects.
3. Sec 2.2 – the title says "formal practices in tinkering". Isn't this a misnomer? I think tinkering is meant to be "informal".	Thank you for the comment. The motivation behind this section heading was to talk about formal problem-solving practices associated with tinkering.
4. Sec 2.5, 1st sentence – seems to be quite strong without much support in the preceding discussion.	Thank you for the comment. The sentence "The review of the literature in this chapter (chapter 2) has shown that tinkering is a valuable tool/strategy for solving engineering design problems and learners should engage in tinkering" is valid and relevant. Tinkering has value in solving engineering design problems has been discussed in 2.4 and especially in 2.4.3. There is an alignment in the requirements for an engineering design problem and what tinkering allows. Section 2.4.1 presents the alignment of both of these practices as follows "When comparing the characteristics of ill-structured problem solving with that of tinkering, we see that ill-structured problem solving is known to be influenced by context (Jonassen, 2000) and tinkering has been known to happen in context (Baker et al., n.d.). Ill-structured problem-solving requires interacting with the environment (Fernandes & Simon, 1999; Jonassen, 2000), and when people tinker, they interact with their goals (which are based on the problem requirement) and environment while they are working in it (Baker et al., n.d.; Godwin et al., 2016). Ill-structured problem-solving requires external scaffolding or support to sustain for problem-solving processes (Fernandes & Simon, 1999; Kothiyal, 2014), whereas tinkering is sustained by dialogue between the tinkerer's goals and actions they take in the physical space, which scaffold's their problem-solving process (Resnick & Robinson, 2017). Ill-structured problem-solving sometimes involves creating and using external representations, which play an important role in reducing ambiguity (Kothiyal, 2014). Tinkering emphasises the creation of artefacts and performing

	an action to attain desired goals (Vossoughi & Bevan, 2014). Ill-structured problems have incomplete ambiguous goals (Kothiyal, 2014), and goals in tinkering can accommodate the ambiguity as they could be prescribed or emergent, which may shift over time (Turkle & Papert, 1990)."
5. Sec 2.6, 1st sentence - the gap is not very clear. A more focused discussion on the problem of current practices in engineering design should have been better.	Thank you for the comment. Section 2.6 just summarises Chapter 2. The gaps have been explicitly discussed in section 2.5.
Sec 3.4, 2nd para, pg 36, 5th line – what is "lower bound sample"?	Thank you for the question. A lower bound sample is a sample on the lower boundary of the spectrum of the participants we have designed our solution for. In this case, we were recruiting participants from pre-engineering and above; hence the participant from std 9 was considered a lower bound. Whereas a 4th year UG candidate would be considered a higher bound if we were limiting the participants only to UG engineering courses.
2. Sec 3.7, 1st sentence - argument not very clear. Difference of DBR with other standard research methods is not very clear.	Thank you for the comment. Section 3.7 is the summary section of the third chapter. The difference between DBR and DDR and BDIR has been discussed in detail in section 3.1, where it is stated that DBR aims for "refinement of problems, solutions, methods, and design principles which is in line with the objectives of our research".
Table 4.2 - the table content is not very clear. Is it created by you or already mentioned in the lectures? More explanation needed.	Thank you for the comment. Table 4.2 has been created after analysing the expert data. The objective of the table is to give a summary of various observations and implications from the experts classified among
2. Pg 51, 3rd para, 1st sentence ("To conclude ...") – isn't that quite obvious and well known? Do we really need to perform an elaborate study to find out the obvious?	Thank you for the comment. The study that has been discussed before is an exploratory study. The focus of this study was to observe what happens when learners are given open-ended problems with and without the intervention of a mentor. The statement is, "To conclude, we realise that tinkering is favoured when there is seamless interaction with the availability of information and triggers through a mentor. The mentor's role here is of a non-contributing participant who lets the participant have agency on the solution and the problem-solving process and scaffolds him/her with operational information, reflective questions and prompts". Here the importance of seamless interactions and

	the availability of information in tinkering kits is what has been conveyed. Secondly, the need and role of a mentor for problem-solving with tinkering have not been explored earlier. After this study, we were able to understand the various roles and the situations where the role of a mentor was important. Hence the roles a mentor can take while being a non contributing participant is non-obvious and something that was not known to us through literature.
3. Sec 4.3.2 – not very clear the need for “Xpreseve”. Significant differences with the other models and the gain obtained should have been discussed in more detail.	Thank you for the comment. There was a need for a pedagogy which not only focuses on the learning aspects of exploration and play but also on the evolution of the ideas which is essential for problem-solving. The same has been discussed in gaps in section 2.5
Sec 5.1.2 – mostly repetitive content and could have been much shorter.	Thank you for the comment. 5.1.2 Discusses the basis and processes of selecting the problems that were later chosen to be given during the studies. This section addressed the second comment. The problems that have been chosen subscribe to the requirements for tinkering and also engineering design. These problems have been selected after trying a number of various other problems considering the resources available. There may seem repetitions as earlier the discussion was about the nature of the problems for tinkering, but this section talks about the specifics of the problems that have been chosen.
2. Sec 5.4.5 – mostly anecdotal evidence used to reach a conclusion. No objective evaluation and comparison with other methods are there. Ideally, those should have been done.	Thank you for the comment. Section 5.4.5 summarises and concludes chapter 5. The evidence that has been provided has been arrived at by using the methods of interaction analysis, which has been discussed in detail in section 5.2. As the research aimed to understand the interactions between the participants, the resources and the mentors through their actions and discussions we chose qualitative analysis. The aim of the research was to evaluate the role of the features of the learning environment in nurturing tinkering, which did not require any comparative analysis with any other learning environment and method. Additionally in this section, the focus was on finding evidence for the design conjectures which help establish the role of the features of the tinker in supporting the mediating processes of tinkering, which have been discussed extensively in

	section 4.3.4.
3. Chapters 5 & 6 could have been merged. There are lots of repetitions and verbose descriptions, which could have been avoided.	Thank you for the comment. Chapter 5 and chapter 6 both discuss two different cycles of DBR. The objective of chapter 5 has been to address the design conjectures whereas chapter 6 has been to address the challenges in chap 5 (DBR1) and also address the theoretical conjectures. The content might seem repeated as a few design conjectures for whom evidence was not found, lead to modification of the features and new design conjecture which might seem similar to the ones on chapter 5 (DBR1). Additionally in both the cycles of DBR the method of analysis remains the same but the conjectures that are being evaluated are very different.
Sec 7.4 – is this section really required? The claims seem to be obvious. Is there something that is non-trivial?	Thank you for the comment. This section talks about the claims of the thesis, There are four claims. The first is "Design features of Tinkery 1.0 and 2.0 along with the Xpresev pedagogy nurture tinkering when solving engineering design problems". The entire thesis was about designing a learning environment for tinkering without a pedagogy and concrete guidelines to design a learning environment. Hence, being able to design a learning environment and provide evidence for it being able to nurture tinkering is an important claim. The second claim made is "Supporting a sense of agency of the learner in the problem-solving process is essential to nurture tinkering for problem-solving. The role of each element of the learning environment should be designed to support the learner in whatever they want to do.". This is something that was observed in our studies, and the features of the learning environment allowed the learners agency. This has been different from the traditional labs and some tinkering labs nationwide. Most engineering design labs and tinkering-based learning environments need to consider such learner-centric perspectives; hence, this conduction is non-trivial given the current state of the lambs-based activities in engineering colleges and some tinker labs. The third claim made is "Building ideas physically as artefacts and performing actions on those artefacts while situated in the problem space eases

2. Sec 7.4, last claim ("A mentor ...") - is it always necessarily so or desirable? Mentors can bias thinking of the tinkerer, possibly leading to an outcome not reflective of the tinkerer's biassed thinking of the tinkerer, possibly leading to an outcome not reflective of the tinkerer's thinking process.	the problem-solving process for learners." As mentioned before, this was again observed during the studies. The emphasis on building something physically situated in a real-life context is absent in most engineering labs where the problems they work on are generic and have scripted solutions. Secondly, as we observed in the explorative study and discussed in the literature, engineers have been trained to follow a systematic by-the-book approach missing the cycles of exploration and play. Even if they happen, they are done based on ideas, and physical actions only appear in the end. Hence the claim that building ideas physically in short cycles of exploration and play is important and non-trivial as it should be emphasised in engineering design as much as it should. The last claim is for a mentor stating, "A mentor can aid the nurturing of tinkering for problem-solving as a non-contributing participant by providing reflection prompts, triggers for actions and checks, assurances and allowing the learners to learn from failure." Thinkering was known to be a loner's activity until recently when researchers started exploring the role of collaboration. As it has been pointed out, the lab mentors were either leading the learners to a solution based on their experiences or limiting their exploration. There was a need for a mentor to break fixations and trigger reflections. Hence we defined the role of mentor as a non-contributing participant as they are equally involved but do not participate in the solving process. Their role is limited to providing reflective prompts when the learners seem stuck. Or providing available factual information, which is a feature we are trying to automate, as discussed in Appendix C. Since the guidelines to the mentor ensure that they do not interfere with the problems solving but scaffold their tinkering process, I believe it is not a trivial claim.
3. Sec 8.1.4 – the guidelines are presented in very generic terms, making it difficult to appreciate novelty. Is there anything that is not already well-known or obvious? If so, those should be highlighted.	Thank you for the comment. This section talks about guidelines for designing a tinkerable learning environment. The guidelines have been collated and aligned and are written in this format so that they can be applicable to a wide variety of contexts and problems and are not limited to engineering design in robotics. The guidelines may resemble the different various works of literature from different

<table>
<tr><td></td><td>contexts that they have derived or collated from, but these are not something that is known in the problem-solving literature of engineering design.,</td></tr>
<tr><td>Sec 8.2 – the whole section seems to be an afterthought and doesn’t fit at this place. I think these can be put under Ch 2 (related work) or as appendix.</td><td rowspan="2">Thank you for the comment. Chapter 7 presents the discussions on the findings and shows how the findings are placed in the current literature and have contributed to the existing body of research and literature. Whereas Chapter 8 concludes the thesis by presenting the contributions and how different groups, like researchers and practitioners, can benefit from them. It also presents the spinoff research topics that have been carefully thought and investigated as possible features in a learning environment. These have been discussed briefly, and details have been mentioned in Appendix C.</td></tr>
<tr><td>5. Chapters 7 & 8 can be merged. There are lots of repetitions and verbose descriptions, which could have been avoided.</td></tr>
</table>

References

Adamson, B., & Walker, E. (2011). Messy collaboration: Learning from a Learning Study. *Teaching and Teacher Education*, *27*(1), 29–36.

ATL. (2019). Atal Tinker Labs. https://aim.gov.in/atl.php#:~:text=About%20Atal%20Tinkering%20Labs&text=The%20objective%20of%20this%20scheme,adaptive%20learning%2C%20physical%20computing%20etc.

Atman, C. J., & Bursic, K. M. (1996). Teaching engineering design: Can reading a textbook make a difference? *Research in Engineering Design*, *8*(4), 240–250.

Baker, D., Krause, S., & Purzer, S. (n.d.). Developing An Instrument To Measure Tinkering And Technical Self Efficacy In Engineering. In *2008 Annual Conference & Exposition Proceedings*. https://doi.org/10.18260/1-2--3413

Berland, M. (2016). Making, tinkering, and computational literacy. *Makeology*. https://doi.org/10.4324/9781315726496-12/making-tinkering-computational-literacy-matthew-berland

Bevan, B., Gutwill, J. P., Petrich, M., & Wilkinson, K. (2015). Learning through STEM-rich tinkering: Findings from a jointly negotiated research project taken up in practice. *Science Education*, *99*(1), 98–120.

Bevan, B., Petrich, M., & Wilkinson, K. (2014). Tinkering is serious play. *Educational Leadership: Journal of the Department of Supervision and Curriculum Development, N.E.A*, *72*(4), 28–33.

Beyer, H., & Holtzblatt, K. (1998). *Contextual Design: Defining Customer-Centred Systems*. Morgan Kaufmann.

Bhatti, Y. (2013). Jugaad Innovation: Think Frugal, Be Flexible, Generate Breakthrough Growth. *South Asian Journal of Global Business Research*, *2*(2), 279–282.

Blikstein. (2013). Digital fabrication and “making”in education: The democratisation of invention. *FabLabs: Of Machines, Makers and Inventors*. https://ccst.us/wp-content/uploads/pblikstein-democratizinginvention.pdf

Brahms, L., & Werner, J. (2013). Designing Makerspaces for Family Learning in Museums and Science Centers. In M. Honey & D. E. Kanter (Eds.), *Design, Make, Play - Growing the next generation of STEM Innovators* (pp. 89–112).

Bransford, J. D., Sherwood, R. D., Hasselbring, T. S., Kinzer, C. K., & Williams, S. M. (1990). *Anchored Instruction: Why We Need It and How Technology Can Help* (pp. 129–156). Routledge.

Brown, J. S., Collins, A., & Duguid, P. (1989, January 1). Situated Cognition and the Culture of Learning. *Educational Researcher*, *18*(1), 32–42.

Cheng, Y.-W., Sun, P.-C., & Chen, N.-S. (2017). An Investigation of the Needs on Educational Robots. In *2017 IEEE 17th International Conference on Advanced Learning Technologies (ICALT)*. https://doi.org/10.1109/icalt.2017.115

Ching, Y.-H., Hsu, Y.-C., & Baldwin, S. (2018). Developing Computational Thinking with Educational Technologies for Young Learners. *TechTrends*, 1–11.

Collins, A., Brown, J. S., Newman, S. E., BBN LABS INC CAMBRIDGE MA., & Bolt, Beranek, and Newman. (1986). *Cognitive Apprenticeship: Teaching the Craft of Reading, Writing and Mathematics*. University of Illinois.

Dougherty, D. (2013). The Maker Mindset. In M. Honey & D. E. Kanter (Eds.), *Design, Make, Play Growing the next generation of STEM Innovators* (pp. 25–29). Routledge.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *94*(1), 103–120.

Fernandes, R., & Simon, H. A. (1999). A study of how individuals solve complex and ill-structured problems. *Policy Sciences*, *32*(3), 225–245.

Godwin, A., Potvin, G., Hazari, Z., & Lock, R. (2016). Identity, Critical Agency, and Engineering: An Affective Model for Predicting Engineering as a Career Choice. In *Journal of Engineering Education* (Vol. 105, Issue 2, pp. 312–340). https://doi.org/10.1002/jee.20118

Goswami, U., Leevers, H., Pressley, S., & Wheelwright, S. (1998). Causal reasoning about pairs of relations and analogical reasoning in young children. *The British Journal of Developmental*

Psychology, *16*(4), 553–569.

Guindon, R. (1990). Designing the Design Process: Exploiting Opportunistic Thoughts. *Human–Computer Interaction*, *5*(2-3), 305–344.

Happonen, A., Minashkina, D., Nolte, A., & Angarita, M. A. M. (2020). Hackathons as a company – University collaboration tool to boost circularity innovations and digitalization enhanced sustainability. *PROCEEDINGS OF THE 15TH INTERNATIONAL CONFERENCE ON MESON-NUCLEON PHYSICS AND THE STRUCTURE OF THE NUCLEON*. PROCEEDINGS OF THE 15TH INTERNATIONAL CONFERENCE ON MESON-NUCLEON PHYSICS AND THE STRUCTURE OF THE NUCLEON, Pittsburgh, PA, USA. https://doi.org/10.1063/5.0001883

Harris, E., Winterbottom, M., Xanthoudaki, M., Calcagnini, S., & De, P. I. (2017). *Tinkering A practitioner guide for developing and implementing tinkering activities*. TINKERING IN THE EU, Open Educational Resources.

Harris, E., Winterbottom, M., Xanthoudaki, M., Calcagnini, S., & de Pijer, I. (2016). *A PRACTITIONER GUIDE FOR DEVELOPING AND IMPLEMENTING TINKERING ACTIVITIES*. Tinkering Contemporary Education for Innovators of Tomorrow Project.

Hesse, F. W., & Klecha, D. (1990). Use of analogies in problem solving. *Computers in Human Behavior*, *6*(1), 115–129.

Hielscher, S., & Smith, A. (2014). *Community-Based Digital Fabrication Workshops: A Review of the Research Literature*. https://doi.org/10.2139/ssrn.2742121

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review*. https://doi.org/10.1023/B:EDPR.0000034022.16470.f3

Honey, M., & Kanter, D. E. (2013). *Design, Make, Play: Growing the Next Generation of STEM Innovators*. Routledge.

Hutchins, E. (2000). *Distributed Cognition*. arl.human.cornell.edu. https://arl.human.cornell.edu/linked%20docs/Hutchins_Distributed_Cognition.pdf

Ibáñez, M.-B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review.

Computers & Education.

Jain, S. (2022). From jugaad to jugalbandi: Understanding the changing nature of Indian innovation. *Asia Pacific Journal of Management*, *39*(1), 1–26.

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies*, *12*(1), 3–11.

Jonassen, D. H. (1997). Instructional design models for well-structured and III-structured problem-solving learning outcomes. In *Educational Technology Research and Development* (Vol. 45, Issue 1, pp. 65–94). https://doi.org/10.1007/bf02299613

Jonassen, D. H. (2000). Toward a design theory of problem solving. *Educational Technology Research and Development: ETR & D*, *48*(4), 63–85.

Jordan, B., & Henderson, A. (1995). Interaction Analysis: Foundations and Practice. *Journal of the Learning Sciences*, *4*(1), 39–103.

Jung, S. E., & Won, E.-S. (2018). Systematic Review of Research Trends in Robotics Education for Young Children. *Sustainability: Science Practice and Policy*, *10*(4), 905.

Kantorovich, A. (1993). *Scientific Discovery: Logic and Tinkering*. SUNY Press.

Karim, M. E., Lemaignan, S., & Mondada, F. (2015). A review: Can robots reshape K-12 STEM education? *Advanced Robotics and Its Social Impacts (ARSO), 2015 IEEE International Workshop on*, 1–8.

Kirsh, D., & Maglio, P. (1994). On distinguishing epistemic from pragmatic action. *Cognitive Science*, *18*(4), 513–549.

Knowles, J. R. (1987). Tinkering with Enzymes: What Are We Learning? *Science*, *236*(4806), 1252–1258.

Kothiyal, A. (2014). Notes on problem solving: A literature review of problem-solving, with emphasis on ill-structured, engineering and estimation problems. *Indian Institute of Technology, Bombay, Technical*.

Lamers, M. H., Verbeek, F. J., & van der Putten, P. W. H. (2013). Tinkering in Scientific Education. *Advances in Computer Entertainment*, 568–571.

Lave, J., & Wenger, E. (1991). *Situated Learning: Legitimate Peripheral Participation*. Cambridge

University Press.

Lego. (2019). *Lego Mindstorm Robotics kit*.

Lewis, T. E., & Thurman, J. (2019). Tinkering and Hacking With Objects in the Art Classroom. *Art Education*, *72*(4), 23–28.

Linsey, J. S., Tseng, I., Fu, K., Cagan, J., Wood, K. L., & Schunn, C. (2010). A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty. *Journal of Mechanical Design*, *132*(4), 041003.

Louridas, P. (1999). Design as bricolage: anthropology meets design thinking. *Design Studies*. https://www.sciencedirect.com/science/article/pii/S0142694X98000441

Maker Fair. (2013). https://make.co/

Maloney, D. P. (2011). An overview of physics education research on problem solving. *Getting Started in PER*.

Martinez, S. L., & Stager, G. (2013). *Invent to learn: Making, tinkering, and engineering in the classroom*. Constructing modern knowledge press Torrance, CA.

Martin, T., & Schwartz, D. L. (2005). Physically distributed learning: adapting and reinterpreting physical environments in the development of fraction concepts. *Cognitive Science*, *29*(4), 587–625.

McKenney, S., & Reeves, T. C. (2014). Educational Design Research. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop (Eds.), *Handbook of Research on Educational Communications and Technology* (pp. 131–140). Springer New York.

Mol, A., Moser, I., & Pols, J. (2015). *Care in Practice: On Tinkering in Clinics, Homes and Farms*. transcript Verlag.

National Research Council, Division of Behavioral and Social Sciences and Education, Board on Behavioral, Cognitive, and Sensory Sciences, & Committee on Developments in the Science of Learning with additional material from the Committee on Learning Research and Educational Practice. (2000). *How People Learn: Brain, Mind, Experience, and School: Expanded Edition*. National Academies Press.

Next Robotics. (n.d.). Next Robotics. http://www.nextroboticslab.in/next-robotics-lab.html

NITI Ayog Govt of India. (2019, September 15). *Atal Tinker Labs*. Atal Innovation Mission. https://www.aim.gov.in/hubs-of-innovation.php

Parisi, S., Rognoli, V., & Sonneveld, M. (2017). Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education. *The Design Journal*, *20*(sup1), S1167–S1184.

Patton, M. Q. (2014). *Qualitative Research & Evaluation Methods: Integrating Theory and Practice*. SAGE Publications.

Peppler, K. (2013). STEAM-powered computing education: Using e-textiles to integrate the arts and STEM. *Computer*, 1.

Peppler, K. (2016). Remaking Arts Education Through Physical Computing. In *Makeology* (pp. 206–225). https://doi.org/10.4324/9781315726496-13

Peppler, K., Halverson, E., & Kafai, Y. B. (2016a). *Makeology: Makerspaces as Learning Environments (Volume 1)*. Routledge.

Peppler, K., Halverson, E. R., & Kafai, Y. B. (2016b). *Makeology: Makers as Learners (Volume 2)*. Routledge.

Petrich, M., Wilkinson, K., & Bevan, B. (2013). It Looks Like Fun, but Are They Learning? In M. Honey & D. E. Kanter (Eds.), *Design, Make, Play Growing the next generation of STEM Innovators* (Vol. 1, pp. 68–88). Routledge.

Petrich, M., Wilkinson, K., & Bevan, B. (2017). *Learning Dimensions of Making and Tinkering: A professional development tool for educators* (Version 1). The tinkering studio, Exploratorium. https://www.exploratorium.edu/sites/default/files/files/Learning%20Dimensions%20of%20Making%20and%20Tinkering.pdf

Prabhu, J., Ahuja, S., Radjou, N., & Roberts, K. (2013). *Jugaad Innovation: Think Frugal, Be Flexible, Generate Breakthrough Growth*.

Pretz, J. E., Naples, A. J., & Sternberg, R. J. (2003). Recognizing, defining, and representing problems.

The Psychology of Problem Solving, *30*(3). https://books.google.com/books?hl=en&lr=&id=zm_lucJyrakC&oi=fnd&pg=PA3&dq=+Recognizing,++defining,++and+representing+problems.+&ots=mHanOf-dM8&sig=DYwWRviLjZuAtvmfWwZXZwfn5AQ

Puntambekar, S. (2018). Design-Based Research (DBR). In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International Handbook of the Learning Sciences*. Routledge.

Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design Studies*, *17*(4), 363–383.

Quan, G., & Gupta, A. (2019). Tensions in the productivity of design task tinkering. *The Research Journal of Engineering Education*, *109*(1), 88–106.

Quintana, C., Zhang, M., & Krajcik, J. (2005). A Framework for Supporting Metacognitive Aspects of Online Inquiry Through Software-Based Scaffolding. *Educational Psychologist*, *40*(4), 235–244.

Ragnoli, M., Colaiuda, D., Leoni, A., Ferri, G., Barile, G., Rotilio, M., Laurini, E., De Berardinis, P., & Stornelli, V. (2022). A LoRaWAN Multi-Technological Architecture for Construction Site Monitoring. *Sensors* , *22*(22). https://doi.org/10.3390/s22228685

Regalla, L. (2016). Developing a Maker Mindset. In K. Peppler, E. R. Halverson, & Y. B. Kafai (Eds.), *Makeology Makerspaces as Learning Environments* (Vol. 1, pp. 257–272). Routledge.

Resnick, M. (2007). All I really need to know (about creative thinking) I learned (by studying how children learn) in kindergarten. *Proceedings of the 6th ACM SIGCHI Conference on*. https://dl.acm.org/citation.cfm?id=1254961

Resnick, M., & Robinson, K. (2017). *Lifelong Kindergarten: Cultivating Creativity Through Projects, Passion, Peers, and Play*. MIT Press.

Resnick, M., & Rosenbaum, E. (2013). *Designing for Tinkerability. Design, Make, Play: Growing the Next Generation of STEM Innovators, 163-181*. Routledge.

Ringwood, J. V., Monaghan, K., & Maloco, J. (2005). Teaching engineering design through Lego® Mindstorms. *European Journal of Engineering Education*, *30*(1), 91–104.

Rognoli, V., & Parisi, S. (2021). *Material Tinkering and Creativity*.

https://re.public.polimi.it/handle/11311/1164648

Ruzzenente, M., Koo, M., & Nielsen, K. (2012). A review of robotics kits for tertiary education. *Teaching Robotics …*. https://www.academia.edu/download/24905167/trtwr2012_submission_25.pdf

Sandoval, W. (2014). Conjecture Mapping: An Approach to Systematic Educational Design Research. *Journal of the Learning Sciences*, *23*(1), 18–36.

Sekhsaria, P. (2018). *Instrumental Lives: An Intimate Biography of an Indian Laboratory*. Routledge.

Sheridan, K., Halverson, E. R., Litts, B., Brahms, L., Jacobs-Priebe, L., & Owens, T. (2014). Learning in the making: A comparative case study of three makerspaces. *Harvard Educational Review*, *84*(4), 505–531.

Smith, P. K., & Roopnarine, J. L. (2018). *The Cambridge Handbook of Play: Developmental and Disciplinary Perspectives*. Cambridge University Press.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285.

Teacher training, ATL. (2016). Teacher Training Module ATL. https://aim.gov.in/atl-teacher-training-modules.php

Turkle, S., & Papert, S. (1990). Epistemological pluralism: Styles and voices within the computer culture. *Signs: Journal of Women in Culture and Society*, *16*(1), 128–157.

UNESCO. (2022). *K-12 AI curricula: A mapping of government-endorsed AI curricula* (No. ED-2022/FLI-ICT/K-12). UNESCO.

Viswanathan, V., Atilola, O., Esposito, N., & Linsey, J. (2014). A study on the role of physical models in the mitigation of design fixation. *Journal of Engineering Design*, *25*(1-3), 25–43.

Viswanathan, V., & Linsey, J. (2013). Examining design fixation in engineering idea generation: the role of example modality. *International Journal of Design Creativity and Innovation*, *1*(2), 109–129.

Vossoughi, S., & Bevan, B. (2014). Making and tinkering: A review of the literature. *National Research Council Committee on Out of School Time STEM*, 1–55.

Vossoughi, S., Escudé, M., Kong, F., & Hooper, P. (2013). Tinkering, learning & equity in the after-school setting. *Annual FabLearn Conference. Palo Alto, CA: Stanford University*. https://www.academia.edu/download/47653916/Vossoughi_Escude_Kong_Hooper_TinkeringLearning_Equity_2013.pdf

Wang, J., Werner-Avidon, M., Newton, L., Randol, S., Smith, B., & Walker, G. (2013). Ingenuity in Action: Connecting Tinkering to Engineering Design Processes. *Journal of Pre-College Engineering Education Research (J-PEER)*, *3*(1), 2.

Wargo, J. M. (2018). Lights! Cameras! Genders? Interrupting hate through classroom tinkering, digital media production and [Q]ulturally sustaining arts-based inquiry. *Theory into Practice*, *58*(1), 1–11.

Wilkinson, K., Anzivino, L., & Petrich, M. (2016). The Big Idea Is Their Idea. In K. Peppler, E. R. Halverson, & Y. B. Kafai (Eds.), *Makeology, Makers as Learners* (Vol. 2, pp. 161–179). Routledge.

Wilkinson, K., & Petrich, M. (2013). *The Art of tinkering: meet 150+ makers working at the intersection of art, science & technology*. Weldon Owen.

Yin, R. K. (2017). *Case Study Research and Applications: Design and Methods*. SAGE Publications.

Zaphiris, P., & Ioannou, A. (2021). *Learning and Collaboration Technologies: New Challenges and Learning Experiences: 8th International Conference, LCT 2021, Held as Part of the 23rd HCI International Conference, HCII 2021, Virtual Event, July 24–29, 2021, Proceedings, Part I*. Springer Nature.

Zhang, L., & Nouri, J. (2019). A systematic review of learning computational thinking through Scratch in K-9. *Computers & Education*, *141*, 103607.

Radjou, Navi, Jaideep Prabhu, and Simone Ahuja. Jugaad innovation: Think frugal, be flexible, generate breakthrough growth. John Wiley & Sons, 2012.

Jauregui, Beatrice. "Provisional agency in India: Jugaad and legitimation of corruption." American Ethnologist 41.1 (2014): 76-91.

Rai, Amit S. Jugaad time: Ecologies of everyday hacking in India. Duke University Press, 2019.

Birtchnell, Thomas. "Jugaad is a systemic risk and disruptive innovation in India." Contemporary South Asia 19.4 (2011): 357-372.

Wilkinson K, Petrich M. The Art of tinkering: meet 150+ makers working at the intersection of art, science & technology. Weldon Owen; 2013.

Dym CL, Agogino AM, Eris O, Frey DD, Leifer LJ. Engineering design thinking, teaching, and learning. Journal of engineering education. 2005;94: 103–120.

Roth, W. M. (1996). Art and artifact of children's designing: A situated cognition perspective. Journal of the Learning Sciences, 5(2), 129–166. https://doi.org/10.1207/s15327809jls0502_2

Berland, M., Martin, T., Benton, T., Petrick Smith, C., & Davis, D. (2013). Using learning analytics to understand the learning pathways of novice programmers. Journal of the Learning Sciences, 22(4), 564–599. https://doi.org/10.1080/10508406.2013.836655

Brown, T. (2008). Design thinking. Harvard Business Review, 86(6), 84–141

Guerra, L., Allen, D. T., Crawford, R. H., & Farmer, C. (2012). A unique approach to characterizing the engineering design process. Paper presented at the American Society for Engineering Education, San Antonio, TX. Retrieved from https://peer.asee.org/a-unique-approach-to-characterizing-the-engineering-design-process.pdf

Baker, D., & Krause, S., & Purzer, S. (2008, June), Developing an instrument to measure tinkering and technical self efficacy in engineering. Paper presented at the ASEE Annual Conference & Exposition, Pittsburgh, Pennsylvania.

Godwin, A., Potvin, G., Hazari, Z., & Lock, R. (2016). Identity, critical agency, and engineering: An affective model for predicting engineering as a career choice. Journal of Engineering Education, 105(2), 312–340. https://doi.org/10.1002/jee.20118

Godwin, A., Sonnert, G., & Sadler, P. M. (2016). Disciplinary differences in out-of-school high school science experiences and influence on students' engineering choices. Journal of Pre-College Engineering Education Research, 6(2), 25–38.

Lyons, L., Tissenbaum, M., Berland, M., Eydt, R., Wielgus, L., & Mechtley, A. (2015). Designing visible engineering: Supporting tinkering performances in museums. In Proceedings of the 14th International Conference on Interaction Design and Children, Medford, MA

Resnick, M., & Rosenbaum, E. (2013). Designing for tinkerability. In M. Honey & D. Kanter (Eds.), Design. Make. Play: Growing the next generation of STEM innovators (pp. 163–181). New York, NY: Routledge

Vossoughi, S., Escudé, M., Kong, F., & Hooper, P. (2013). Tinkering, learning & equity in the after-school setting. Paper presented at the FabLearn Conference, Palo Alto, CA.

Louridas, P. (1999). Design as bricolage: Anthropology meets design thinking. Design Studies, 20(6), 517–535. https://doi.org/10.1016/S0142-694X(98)00044-1

Turkle, S., & Papert, S. (1990). Epistemological pluralism: Styles and voices within the computer culture. Signs, 16(1), 128–157.

Vallgårda, A., & Fernaeus, Y. (2015). Interaction design as a bricolage practice. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction, Palo Alto, CA.

Clapp, E. P., Ross, J., Ryan, J. O., & Tishman, S. (2016). Maker-centered learning: Empowering young people to shape their worlds. San Francisco, CA: John Wiley & Sons.

Martinez, S. L., & Stager, G. (2013). Invent to learn: Making, tinkering, and engineering in the classroom. Torrance, CA: Constructing Modern Knowledge Press.

Wang, J., Werner-Avidon, M., Newton, L., Randol, S., Smith, B., & Walker, G. (2013). Ingenuity in action: Connecting tinkering to engineering design processes. Journal of Pre-College Engineering Education Research, 3(1), 1–21.

Tuminaro, J., & Redish, E. F. (2007). Elements of a cognitive model of physics problem solving: Epistemic games. Physical Review Special Topics-Physics Education Research, 3(2), 020101-1–020101-22. https://doi.org/10.1103/PhysRevSTPER.3.020101
Quan, Gina M., and Ayush Gupta. "Tensions in the productivity of design task tinkering." Journal of Engineering Education109.1 (2020): 88-106.

Jonassen, D. H. (2000). Toward a design theory of problem solving. Educational Technology Research and Development, 48(4), 63–85.

Danielak, B. A., Gupta, A., & Elby, A. (2014). Marginalized identities of sense-makers: Reframing engineering student retention. Journal of
Engineering Education, 103(1), 8–44. http://doi.org/10.1002/jee.20035

Johri, A., & Olds, B. M. (2011). Situated engineering learning: Bridging engineering education research and the learning sciences. Journal of Engineering Education, 100(1), 151–185. https://doi.org/10.1002/j.2168-9830.2011.tb00007.x

Resnick M. Lifelong Kindergarten: Cultivating Creativity Through Projects, Passion, Peers, and Play. MIT Press; 2017.

Kirsh, David, and Paul Maglio. "On distinguishing epistemic from pragmatic action." Cognitive science 18.4 (1994): 513-549.

Louridas P. Design as bricolage: anthropology meets design thinking. Design Studies. 1999; Available: https://www.sciencedirect.com/science/article/pii/S0142694X98000441

Lévi-Strauss C, Others. La pensée sauvage. Plon Paris; 1962.

Quintana, Chris, et al. "A scaffolding design framework for software to support science inquiry." The journal of the learning sciences 13.3 (2004): 337-386.

Siegler, Robert S., and Matija Svetina. "What leads children to adopt new strategies? A microgenetic/cross-sectional study of class inclusion." Child Development 77.4 (2006): 997-1015.

List of Publications

Raina, Ashutosh, Sridhar Iyer and Sahana Murthy. "Tinkery: A Tinkerer's Nursery for Problem Solving with Lego Mindstorms", *In Proceedings of the 29th International Conference on Computers in Education. Asia-Pacific Society for Computers in Education. ICCE 2021.*

Jain,Shruti, **Raina, Ashutosh**, Iyer, Sridhar, "TinkerBot: A Semi-Automated Scaffolding Agent as a Companion for Tinkering", *In Proceedings of the 29th International Conference on Computers in Education. Asia-Pacific Society for Computers in Education. ICCE 2021.*

Raina, Ashutosh, Sridhar Iyer and Sahana Murthy. "Developing Computational Thinking Through Tinkering in Engineering Design", *2020 Fourth international Conference on Computational Thinking Education.*

Raina, Ashutosh, Sahana Murthy, and Sridhar Iyer. "Designing Tink-Mate: A Seamless Tinkering Companion for Engineering Design Kits" *2019 IEEE Eleventh International Conference on Technology for Education (T4E)*. IEEE, 2019.

Raina, Ashutosh, Sahana Murthy, and Sridhar Iyer. "" Help Me Build": Making as an Enabler for Problem Solving in Engineering Design." *2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT)*. IEEE, 2018.

Raina, Ashutosh., Jogeshwar, R., Yadav, Y., & Iyer, S. (under review). "TA to AI: Tinkering Approach to Artificial Intelligence and Computational Thinking Education in Indian Schools". In H. Abelson & S.-C. Kong (Eds.), *Computational Thinking Curricula in K-12: International Implementations.* Cambridge, MA: MIT Press.

Acknowledgments

The satisfaction of presenting this thesis, a story of an adventure, is complete with mentioning people who were part of it - some as figures while some as shadows. They made possible both this academic research and self-discovery. Their constant encouragement and guidance have been a source of inspiration. A heartfelt gratitude to everyone who, directly or indirectly, has been a part of the making of this thesis. A reflection on the genesis of the thought that kindled this doctoral thesis takes me to days I spent with my elders (all teachers by profession and passion), my teachers and professors. Memories of watching them teach them on the humble grounds of the village schools to professors in leading institutes of the country teaching in state-of-the-art labs and classrooms. What I distinctly remember is the effort that some of them made to address the diversity in ways of learning though they were just required to follow a one size fits all method of teaching. They ensured every one of their students learned something that improved their lives. This thesis was inspired by this acknowledgement of believing that every learner has their own way and is authentic to them. In addition, my own experiments with learning engineering "by doing" led me to firmly believe in and pursue research in educational technology. But then I thought, was it even before in the dreams of my grandfathers (late Sri G.L Raina and late Sri R.L Sharma) who laid the foundation, encouraged and supported the importance of education in our families and in the lores of my grandmothers (late Smt. Durga Devi Raina and Smt. Kamla Sharma) or was it in the examples of my parents (Mrs Suman Raina and Prof. P K Raina) who have always inspired, guided, supported me to let me work the paths I choose. I still don't have an answer, but I am grateful for my experiences throughout my journey and its outcome.

My guiding lights and a safety net for this adventurous journey into the unknown have been my mentors, Prof. Sridhar Iyer and Prof. Sahana Murthy, who have believed in my ways and nurtured me to grow as a free yet critical thinker and humble yet confident researcher. They have always pushed me and at times themselves to help me become the person I am today and I hope to be like the teachers they are. Apart from numerous opportunities to grow as a researcher and as a professional, they have guided and supported me through all professional and personal hurdles of my life. I am grateful to them for seeing the best possibilities for me, which I would have never known and am still discovering. Their ways and work inspire me, and I hope I always follow the examples they set as teachers and researchers.

I also thank my RPCs, Prof. Sasikumar M, Prof. B K Chakravarthy & Prof Ritayan Mitra, who believed in my work with their long deep and critical question-answer sessions after every APS. Their questions and suggestions have always helped me to see my thesis (this path) clearer and shaped it with valuable suggestions. Special thanks to Prof. Chandan Dasgupta and Prof Ramkumar, who also helped me focus and direct my thesis through their frequent suggestions and questions. In addition, I would also like to thank Prof. Sanjay Chandrashekhar and Prof. Annirudha Joshi, who, through their courses, helped me develop the basis for carrying out the research work.

Additionally for motivation to pursue PhD I would like to acknowledge my supervisor and mentor from my masters degree, Prof. Divya Bansal of PEC university of technology and Prof. Bhaskaran Raman of IIT Bombay for providing me with opportunities and exposure to state of the art research. For lighting the spark for research by motivating me to present a very first research paper I would like to acknowledge Prof. Chidananda Murthy P my advisor and mentor from my bachelors degree.

I can't thank enough my dept IDP in Educational Technology and my institute Indian Institute of Technology Bombay, a beautiful green campus, for world-class facilities that made my life easier and assisted me in focusing on my work. Without hesitation, I can call this institute my second home, which provides a healthy work-study environment to grow and shine. I thank the staff of the IDP Educational Technology department and of IIT Bombay for their constant support, time and assistance in handling administrative work, especially Mrs Seema, Ms Pallavi, Mr Prakash, Mr Ajit and Ms Asha. I acknowledge my anonymous reviewers and editors of my manuscripts for their comments, improving my analysis and writing skills, which are crucial tools for productive research output. Also, I would like to thank all the participants who agreed to participate in my studies, helping this thesis evolve to where it is now.

I was introduced to my seniors during the student panel interviews; since then, they have been a family. Though no words can justify my gratitude towards them, I make this humble attempt. From the wisdom and guidance of Dr Yogendra(or YPTG as we know him), Dr Kapil (Bhau), Dr Sameer, Dr Madhuri M, Dr Mrinal, Dr Gragi, Dr Rekha, Dr Dipti, Dr Anita and Dr Vikram. Then the mentorship of Dr Jaikrishnan, Dr Rwitojit, Dr Aditi and Dr Shitanshu involved me in hands-on academic activities through their studies, observations and discussions on their analysis. Also, in non-academic domains, like trusting me with management roles in various events and conferences and helping out in all possible ways. Especially Dr Rwitojit for sharing his experiences and passion for photography.

Then Dr Anurag and Dr Kavya as pals as we ran various events like tech connect and the entire designing and running of the NPTEL and SWAYAM course Demystifying Networking a very adventurous and memorable year. As a loner in my 2016 batch, I am grateful to have been a part of the 2015 batch (Dr Lakshmi, Dr Prajish and Soumya) of the department through my initial years as coursemates, lab mates, collaborators, support system supporting me in my professional and personal journey as elder siblings. Also, the 2017 and 2018 batches (Navneet, Pankaj, Rumana, Narasimhan, Lucian, Shiv, Ulfa and Harold) along with (Aastha, Balraj, Kinnari, Shruti, Aditya and Shreya) some who are now my partners in crime as I near completion. They have supported, encouraged and provided a healthy critique of the various academic and non-academic aspects of my journey as a doctoral research scholar. Especially our long discussions - academic and non-academic, emotional and motivational support for each other, and drive of doing things.

All my juniors (Davesh, Alekh, Nandan, David, Vishvanath, Sunita, Archana, Gaurav, Mayank, Deepak, Patishtha and Deepika) for extending their help for various activities and discussions. Additionally (Spruha, Indriyani, Rajshri, Anthony, Amit, Debashree, Ishika, Sumitra, Indra, Vishvas, Jatin, Meera, Nisumbha, Pratiksha, Suprabha, Jyoti, Kabyashree, Ramdas) for their support through their daily conversations and for making me, a super senior, feel part of their group. A special shoutout to our gang of "Lukkhas" who have always been there a call away come what may, and Dr Veenita Shah, who has supported and encouraged my academic endeavours but also extended her unconditional support whenever required helping me and my wife get through tough times. I express my heartiest gratitude to my IITB friends through various committees and acquaintances who became pals – Kaushik, Nirav, Shrabani, Taveen, Deepak, Hassan, Sudip, Sneha, Ankur, Raghav, Malushree and Sarthak

I am so grateful to Kushal and Navneet, for, through Arushi, these total strangers are now friends for life as they have been there throughout this journey, keeping our spirits high by being there for each other and making this journey worth it. We moulded our shortcomings into strengths which helped strengthen our bonds and become who we are today.

This journey also reached its destination because of the unconditional love and support of my family, who have inspired me, taken care of my never-ending needs, and accepted me for the person I am. This long journey sometimes became tiring when these gems of people in my life always stood solid as a rock, for they have been my lifeline and guiding light. My words are not enough to show my gratitude, so I owe them my life – Mummy, Papa, Mummy ji and Dadyji. Additionally to Khyati, Shivam and Puffy I owe them unconditional love and support through every phase of life and a promise to be there always for their happiness, sorrow and tantrums. I extend my heartfelt gratitude to my extended family for all the love and care and to my siblings (Vivek, Hitesh, Jyoti, Parul, Ishan, Abu, Adi, Vibhu, Gopu, Shubhi and Suru) for keeping with my requests even though, I kept postponing almost all the plans you made.

The one who has witnessed this journey along with me and knows me for better or worse is my soulmate - Arushi. She had agreed to share her PhD journey at IIT Bombay but then agreed to trust me with her life. While she figured out her path, she made me move, always by my side. To her, I owe everything from keeping our personal life fulfilling and complete to keeping our professional lives in tandem and in check. From evolving as researchers together to her part in making and sustaining a home. For keeping up with my never-ending tantrums. I can not justify my gratitude for you in words, so I have decided to have you in every acknowledgement of my life. A life which is full of celebration and togetherness.

Last but not least, the almighty for blessing me with the realisation and the people around me, who helped me at every step and enabled me to start and accomplish this journey. I end with a prayer.

ॐ सर्वे भवन्तु सुखिनः
सर्वे सन्तु निरामयाः।
सर्वे भद्राणि पश्यन्तु मा कश्चिद्दुःखभाग्भवेत।
ॐ शान्तिः शान्तिः शान्तिः॥

May all sentient beings be at peace,
May no one suffer from illness,
May all see what is auspicious, and may no one suffer.
Om, peace, peace, peace.

Ashutosh Raina
1/01/2023