BRIDGING CONSTRUCTIONISM & METACOGNITION:

PRODUCTIVE ARTIFACT DOCUMENTATION FOR ELEMENTARY SCHOOL

MAKER EDUCATION

Monica Miaoxia Chan

Teachers College, Columbia University

Submitted in partial fulfillment of the requirements for the
Degree of Doctor of Education in
Teachers College, Columbia University

2022

ABSTRACT

BRIDGING CONSTRUCTIONISM & METACOGNITION: PRODUCTIVE ARTIFACT DOCUMENTATION FOR ELEMENTARY SCHOOL MAKER EDUCATION

Monica Miaoxia Chan

My dissertation is a qualitative design-based research study that explores Singaporean elementary school students' documentation and reflection practices in a maker learning environment. In this work, I build upon literature from Constructionism, Metacognition, and formative assessment methods. I investigate the following research questions regarding student-driven documentation of maker processes:

1) How might artifact documentation and organization, as a mode of formative assessment, provide new insights to students and teachers in complex making/construction processes?
2) How could artifact documentation embedded in a collaborative tool contribute to students' identification and reflection of new knowledge gained during their making process?

Over the course of two and a half years, I developed prototypes of the CoCreator App, informed by constructionist pedagogy and metacognitive practices. Then, I implemented the CoCreator App prototypes in two schools and an afterschool makerspace in Singapore, where students and teachers used it as their technology-facilitated process for documentation. Through analysis of students' and teachers' interviews, observations and field notes of classroom sessions, I reveal opportunities for thoughtful design of documentation tools that advance and challenge the theoretical underpinnings of Constructionism and Metacognition, and cater to elementary school students' learning and reflection. My design recommendations include: multimodal choices of documentation, integration with students' routines and workflows, organization of artifacts to achieve a balance between multimodality and integration with routines. Finally, I end with a note about the essential role that teachers play in engaging with students' artifacts and nurturing a culture of documentation in the classroom, to inch closer to helping students develop intrinsic motivation towards student-driven formative assessment.

Keywords: Maker education, formative assessment, documentation, reflection, Constructionism, Metacognition

TABLE OF CONTENTS

Table of Contents i
List of Tables iii
List of Figures iv
Acknowledgements.......... v

CHAPTER 1. INTRODUCTION.......... 1
Background & Context: Development of K-12 Maker Education.......... 1
Problem Statement.......... 8
Rationale & Significance.......... 10
Statement of Purpose & Research Questions.......... 10
Research approach.......... 11

CHAPTER 2. LITERATURE REVIEW.......... 13
Models of Learning: Cognitivism and Constructivism.......... 13
Formative Assessment & Metacognition.......... 15

CHAPTER 3. RESEARCH METHODOLOGY.......... 23
Research Sample.......... 23
Research Design & Methodology.......... 26
Data Collection Methods.......... 30
Data Analysis Methods.......... 31

CHAPTER 4. FIRST IMPLEMENTATION OF THE COCREATOR APP.......... 34
Phase 1.......... 35
Conception.......... 35
Development of the Preliminary Prototype.......... 37
Implementing Phase 1.......... 38
Findings from Phase 1.......... 38
Phase 2.......... 44
Development of the Prototype.......... 44
Implementing Phase 2.......... 49
Findings from Phase 2.......... 51

CHAPTER 5. SECOND IMPLEMENTATION OF THE COCREATOR APP.......... 66
Key Changes from the First to Second Implementation.......... 66
Design Challenge #1: Providing students with their choice(s) of modality of documentation.......... 66
Design Challenge #2: Understanding the Structure / Analogy of the Tool.......... 67

Design Challenge #3: Representing and communicating social-emotional feelings associated with making……………………………………………………………….. 68
Design Challenge #4: Providing and receiving feedback……………………………….. 68
Phase 3…………………………………………………………………………………… 70
Development of the Prototype………………………………………………………... 70
Implementing Phase 3…………………………………………………………………75
Findings from Phase 3………………………………………………………………... 77

CHAPTER 6. DISCUSSION……………………………………………………………...101
The Importance of Multimodality in Documentation………………………………………102
Integrating with Routines and Workflows………………………………………………. 105
Organization to Achieve Routine with Multimodality…………………………………….. 109
Teachers' Engagement and Facilitation in Students' Documentation Processes …………...110
Sociocultural Norms…………………………………………………………………….. 112

CHAPTER 7. CONCLUSION…………………………………………………………… 114
Limitations…………………………………………………………………………….. 117
Contribution…………………………………………………………………………... 121
Future Work…………………………………………………………………………... 123
Epilogue: Documentation as "Thinking Outside of the Box".. 124

REFERENCES…………………………………………………………………………… 126

APPENDICES…………………………………………………………………………….. 138
Appendix A: Observation Guide for Phases 1, 2 and 3……………………………………138
Appendix B: Interview Protocol (Student) for Phase 1……………………………………. 140
Appendix C: Interview Protocol (Student) for Phase 2……………………………………. 142
Appendix D: Interview Protocol (Maker Educator) for Phase 2…………………………... 144
Appendix E: Interview Protocol (Student) for Phase 3……………………………………. 146
Appendix F: Interview Protocol (Maker Educator) for Phase 3………………………….. 150
Appendix G: Coding Scheme…………………………………………………………… 154
Appendix H: Additional artifacts from Brendan & Iman's project………………………... 157
Appendix I: Dan's Documentation on the CoCreator App and Slack……………………... 158

LIST OF TABLES

Table		Page
1	Program Structure for Phase 1 …………………………………………………	27
2	Program Structure for Phase 2 …………………………………………………	27
3	Program Structure for Phase 3 …………………………………………………	29
4	Students' Projects and Choices of Documentation Modalities at the Informal Makerspace ……………………………………………………………………...	59
5	Changes made in design features from the first to second implementation …….	69
6	Student Groups in Phase 3 …………………………………………………..	76
7	Documentation Styles amongst students: "Leader," "Follower," "Diplomat" …	78

LIST OF FIGURES

Figure		Page
1	Low-fidelity CoCreator App in the form of a concept tool with a solar system analogy (first design iteration) …………………………………………………..	37
2	Hannah's concept map, classified as goal-oriented behavior ……………………	41
3	Valerie's concept map, classified as challenge-oriented behavior ……………….	43
4	Sarah's concept map, classified as top-down procedural visualization behavior ..	44
5	CoCreator App Prototype built on Miro (second design iteration) ……………...	47
6	Brendan and Iman's framework on the CoCreator App, focusing on virtual post-it notes under "Parts," "Materials," and "Build Questions," and connecting arrows between "4 layers" and "4 layers because not too heavy."	53
7	Brendan and Iman sketch their first and second bridge's designs, before and after incorporating synchronous feedback from their teacher regarding ice-cream stick placement to strengthen their bridge design ……………………	54
8	Dan's artifacts about his project Medimind on the CoCreator App ……………..	60
9	Dan's documentation to himself on WhatsApp, integrating tasks from his maker project into his personal to-do list	62
10	The class' most frequently used hashtags on the CoCreator App	73
11	The CoCreator App's interface and features	74
12	Zihao's group's weekly progress chart visualization	81
13	Zihao's photographs of his group's making process and hashtags he used	82
14	Zihao documents as his groupmates code on Scratch and connect the MakeyMakey microcontroller	84
15	Deepak documents his group's activities, with Ivan and Sahil's input	86
16	Dara documents Ivan's activities, then is redirected by Ivan	88

ACKNOWLEDGEMENTS

Thank you to Teachers College and the CMLTD (Communications, Media & Learning Technologies Design) program for providing me the opportunity to explore and pursue my vast interests in the learning sciences and education technology.

First of all, thank you to my dissertation committee for their guidance, advice, and support. My primary faculty advisor, Dr Nathan Holbert, has truly been a pillar of support since my first day at Teachers College. He has nurtured a tight-knit community in the Snow Day Learning Lab that he directs, always has a listening ear to my personal and professional challenges as a graduate student, and has been a role model whom I respect and admire. I am incredibly lucky that my advising experience with Nathan has been so positive, even through the COVID-19 pandemic and juggling 12-13 hour time zone differences when I found myself back at home in Singapore. My secondary faculty advisor, Dr Paulo Blikstein, has mentored me since I was an ebullient undergraduate student back in the day, overly thrilled about anything new that came my way. He was the scholar who introduced me to the field of K-12 Maker Education and the powerful ideas behind Constructionism. He supervised my undergraduate honors thesis at Stanford University on digital fabrication and elementary school engineering education, and encouraged me to become a researcher. He changed my life. My third reader and CMLTD program director, Dr Sandra Okita, has been providing me with academic and life advice about various facets of the doctoral student journey at every step of the way. She is so knowledgeable and kind; my program is fortunate to have her. Finally, I am thankful for my fourth reader Dr Jennifer Lena’s sharp insights and enthusiasm in reviewing the work I’ve been doing over the last 5 years. Thank you, Nathan, Paulo, Sandra, and Jennifer.

Next, thank you to Andrew Zheng, who developed the full stack software for the CoCreator App prototype (Phase 3's design). Straddling major time zone differences during the pandemic, we spent hours discussing implementation, constraints, challenges, last-minute bugs and edits before, during, and after data collection. Synergizing with Andrew has elucidated to me my strengths and weaknesses, and I am grateful for his technical assistance and unwavering patience over the past years.

Thank you to my research assistants at Snow Day Learning Lab - Hongjin Du, Chenyou Wu, Ayse Unal, and Anisa Bora - and the lab's extended community that has provided me with constructive feedback and thoughtful questions. Thank you to my CMLTD doctoral cohort, in whom I have found trustworthy champions: Sawaros (Sam) Thanapornsangsuth, Nicola Law, Yipu Zheng, Isabel Correa, Stephanie Yang, Elliot Hu-Au, Eddie Lin, Shu-Yi Hsu, Marcus Cheung. Of course, thank you Felicia Tersan and Martha Rosas, writing consultants at TC's Graduate Writing Center, for organizing the doctoral writing group to keep me on track, and for reviewing my dissertation.

To my team at TC's Student Senate: Serving on the Senate for four out of five years of my doctoral journey was truly eye-opening. Serving as President of the Student Senate for two years during the pandemic was the largest, most unexpected step out of my comfort zone in my TC experience. My advisors Vice Provost Dr Thomas Rock, former Senior Director of Student Affairs Administration Dr Maria Hataier, Director of Graduate Student Life & Development (GSLD) Denise Boneta, and GSLD Assistant Director Alana Crosby have been excellent mentors. Thank you President Thomas Bailey and Provost Stephanie Rowley for advancing a student-centered mission at TC; I have enjoyed our discussions very much.

I conducted this research at home in Singapore, the country that provided me refuge and a path forward during a tumultuous time in the pandemic. Thank you to Singapore's Ministry of Education for granting me access to local primary schools, and to VIVITA Singapore for welcoming me into their space. Thank you to the teachers, mentors and students who participated in my research - I am constantly amazed with the zest they all have every day.

Thank you to my newfound colleagues and collaborators at the National Institute of Education (Nanyang Technological University) for making me feel at home in the education research community in Singapore, and for introducing me to teachers and administrators to widen my network. Thank you to the National University of Singapore Department of Communications & New Media (CNM) and the Tan Kah Kee Foundation for funding my research with the NUS Development Grant and Tan Ean Kiam Scholarship respectively.

Finally, I thank my parents, Chan Chee Hui and Leong Swee Bee, and my sister, Beatrice Chan, for their encouragement and "so what?" reminders, for this is an essential question to demonstrate research impact. I often think of my late paternal grandmother, a teacher with a secondary school education in a small school in Kahang, a *mukim* (township) in Johor, Malaysia. For most of her life, her technology was blackboard chalk. At her funeral, generations of her students returned to pay their respects. My technologies today are laser cutters, 3D printers, microcontrollers. It is my ardent hope that my work may be as impactful as hers.

Chapter 1. Introduction

I seek to explore a technology-facilitated formative assessment process between elementary school students and teachers in makerspaces, in order to gain new insights about students' documentation processes for interdisciplinary projects and collaboration with teachers to receive and implement feedback. This design-based research study examines how a mobile tool for documentation and organization of artifacts facilitates discussion and feedback between maker educators and elementary school students for their projects. I employ qualitative research methods to illustrate the three-way interaction among the student, teacher, and the formative assessment tool. This study has been segmented into 3 data collection phases: Phase 1 - a preliminary data collection phase with only elementary school students, Phase 2 - data collection involving two research sites (a school and an after-school makerspace), and Phase 3 - data collection one research site (a school, different from Phase 2).

Background & Context: Development of K-12 Maker Education

Decades ago, Piaget conceived the theory of Constructivism (1970), Freire coined the theory of Critical Pedagogy (1972), and later, based on Piaget's Constructivism, Papert formed the theory of Constructionism (1980). Constructionism advances the stance that learning occurs when students create personally meaningful artifacts that can be shared and discussed with their peers and a wider audience (Papert, 1980; Holbert, Berland, Kafai, 2020). Constructionism builds on Constructivism, a developmental psychology theory that Jean Piaget coined in the 20th century, that holds knowledge as actively constructed by learners through experience and ongoing revision of mental models (Papert, 1993; Ackermann, 2001; Sheridan et al., 2014). Constructionism more explicitly focuses on how making external artifacts supports learners' conceptual understanding, and promotes understanding through interpretation of representations

(Papert, 1993). These three frameworks - Constructivism, Critical Pedagogy, and Constructionism - are seminal in the field of the learning sciences, as they theorize how interdisciplinary experiential education happens at various stages of child development, and how such education becomes a tool for understanding personal identity, community, and societal citizenship.

In the 1980s, Logo programming emerged as a tangible avenue to teach students about fundamental computer science and simulations of natural phenomena using a constructivist and constructionist approach (Pea, 1987). Logo was developed at the MIT Media Lab, where Seymour Papert, Wallace Feurzeig, Daniel Bobrow, and Cynthia Solomon pioneered this work (Solomon et al., 2020). Then, at MIT, Mitchel Resnick, Fred Martin, and Stephen Ocko began work combining Logo and LEGO, where they developed a computer-based learning platform that combined LEGO construction with the Logo programming language (Blikstein, 2015). Roy Pea at Stanford University explored cognitive activities that computer programming activities gave rise to in children, including foundation aspects such as debugging, composition, problem understanding, and program design (1987). In the early days of the computer, there were uncertainties around children's conceptual understanding of computing concepts and practices, and there were questions about how to evaluate the complexity and range of cognitive activities that children undergo when they learn programming.

In the 1990s, MIT's Programmable Brick project extended the idea of distributing computational power (ubiquitous computing) and simultaneously targeted the work explicitly at children (Blikstein, 2015). A main objective of ubiquitous computing was to spread computation throughout environments and to embed it in all types of objects, thus the Programmable Brick allowed children to conduct new types of experiments and program autonomous objects. For children, the Programmable Brick became a "thing to think with," in line with the ideals of Constructionism (Blikstein, 2015). It is important to note that the development of technological tools such as Logo and the Programmable Brick are rooted in Constructivism and Constructionism, purely with an intent to investigate how children use and learn with expressive computational tools, rather than an industrial standpoint of preparing students for STEM careers (Granott, 1991, Blikstein, 2015). The Programmable Brick is notable in the history of making and Constructionism, because accessibility to ubiquitous computing contributed to what became the Maker Movement later.

Onwards into the 1990s to 2000s, the Computer Clubhouse at MIT Media Lab was established, and the Scratch coding platform launched (Resnick & Rusk, 1996). The Computer Clubhouse provided a community space for students particularly from lower-income families living in urban settings to work together with adults on personally meaningful projects, using new technologies to tinker and explore, in the spirit of Constructionism (Resnick & Rusk, 1996). This setting was considered an out-of-school informal learning environment, thus there were no rigid structures of assessment based on grades or tests. Instead, through mentorship with adults, students could receive feedback on their projects to continue iterating and improving, which could be considered an informal mode of formative assessment.

During the 2000s, researchers and designers sought to expand participation in maker education and computational literacy to more diverse communities. Education technologies such as the Programmable Brick and microcontrollers were not very accessible in many developing countries. Paulo Blikstein, David Cavallo, and Arnan Sipitakiat developed the GoGo Board, a variant of the Programmable Brick that was low-cost, open source, and easily assembled on-site with simple tools (Blikstein, 2015). As widening access to children and designers from developing countries was a prioritized motivation, the GoGo Board hardware was built to be compatible with international hardware design adaptations (Sipitakiat, Blikstein & Cavallo, 2002; 2004). Children from various countries could thus build tangible projects and use programming languages such as Logo, NetLogo, Java on the GoGo Board, and this provided them the opportunity to engage in maker education more broadly. The introduction of the GoGo board and lower cost tools gave rise to rhetoric around democratization and inclusivity of making, an essential segment of the development of maker education.

Into the 2010s, makerspaces and FabLabs ("fabrication laboratories") started emerging in the K-12 space. Makerspaces often comprise participants of varying ages and levels of experience working with different types of media, and are physical locations where individuals can work independently or collaboratively and use tangible materials to build (Sheridan et al., 2014). Over the past decade, making has emerged as a movement that centers the process of developing an idea, then designing a personally meaningful product, whether physical or digital (Harel & Papert, 1991; Kafai, 2006). The Maker Movement had grown out of longstanding hobbies such as woodworking, sewing and electronics amongst adults, but with the advent of more affordable and accessible digital fabrication tools and online networks, more people are able to participate and share ideas across communities (Martin, 2015).

Making constitutes a spectrum of definitions. For example, Honey and Kanter call making the "design-learn-play" learning methodology (2013). Sheridan and colleagues denote making as the "creative production in art, science, and engineering" (2014). Blikstein and

Krannich describe making in digital FabLabs as merging computation, tinkering and engineering (2013). Kuznetsov and Paulos (2010) define making as DIY (Do It Yourself) practice, which can be viewed “as any creation, modification or repair of objects without the aid of paid professionals,” and Martin establishes making as “a class of activities focused on designing, building, modifying, and/or repurposing material objects, for playful or useful ends” (2015). These activities - digital fabrication, hacking, tinkering, rapid prototyping, DIY etc. - all constitute as *making*. Making has since shifted from a hacking culture at higher education institutions (typically in engineering faculties) to a movement and practice that includes a wider diversity of learners of different backgrounds, ages, and abilities. The Arduino has emerged from the invention of the Programmable Brick, as a lower cost, more versatile tool for ubiquitous computing. More recently, the LilyPad Arduino was created as a fabric-based construction kit to invite novice learners to construct their own wearables and textile artifacts, thus broadening the scope of what computational media entails (Buechley, Eisenberg, Catchen & Crockett, 2008).

Tracing the development of making and tools related to making is relevant, because participation in making has permeated into the K-12 landscape, where interdisciplinary learning occurs while making. Furthermore, documentation and reflection as part of the process of making are valuable practices that add to the learners’ experiences. As we entered the 21st century with greater accessibility to emerging technologies in K-12 education, schools and informal learning organizations have created more spaces and opportunities for hands-on experiential learning, with the optimism that this push towards maker education will prepare students to have a growth-oriented, failure-positive, collaborative mindset (Martin, 2015). In the context of Singapore, where this work takes place, developing growth-oriented and collaborative qualities have been regarded as vital "future-ready skills" (Singapore Ministry of Education, 2015). Over the past decade, the *Maker Movement* has also been popularized by Make Media, a company that introduced the term "makerspace" and promoted the amalgamation of the do-it-yourself (DIY) culture, craft, hacking and hobby fabrication through community programs and Maker Faire events (Cavalcanti, 2013; Dougherty, 2013).

While the Maker Movement had originated amongst adults, there has been growing interest over the past years to bring making into K-12 education to broaden opportunities in STEAM (Science, Technology, Engineering, Art & Mathematics) (Martin, 2015). K-12 maker education researchers draw from Papert's theory of Constructionism. For the purpose of this dissertation and to constrain recruitment of research sites later, I focus on maker education and maker activities that are classified under STEAM, open-ended and ill-structured.

The emergence of makerspaces[1] in K-12 learning environments has led teachers and researchers to explore problem-based and project-based pedagogy in more interdisciplinary settings, while leveraging and incorporating now accessible technologies such as laser cutters and 3D printers into the classroom. Although makerspaces had traditionally been modeled after engineering laboratories primarily for adults (college level and beyond) to use and build technical prototypes, due to recent advancement in technology and decreased costs, makerspaces have expanded to K-12 schools and informal learning environments such as libraries, museums and after-school facilities (Martin, 2015; Dougherty, 2013). Currently, with the increasing variety of networks for maker educators to share ideas and reflections on curriculum development, the academic and practitioner conversation has shifted toward measurement and evaluation of

[1] The term "makerspaces" here encompases various types of spaces that promote collaborative and communal making and sharing, such as FabLabs (fabrication laboratories), hackerspaces, etc.

student learning in makerspaces (Tseng, 2016). Evaluating student learning is necessary to assist students in defining what they know (learner-centered), what they need to know (knowledge-centered), how they can share what they have learned (community-centered) - these are objectives that align with Constructionism (Hadad et al., 2020).

There are fundamental differences in the spirit of assessment for learning in maker education versus traditional test-scoring for individual subject areas. Maker-oriented pedagogy highlights its process-oriented, rather than outcome-oriented, nature (Bevan, Petrich & Wilkinson, 2014; Duffalo, 2010; Ackermann, 2004). Formative assessment methods such as providing observational, informal feedback and implementing revision opportunities as part of the classroom makerspace culture will allow makerspaces to be assessment-centered in a productive manner for students to continue exploring and iterating on their project (Hadad et al., 2020).

Scholars have also addressed that assessment methods need to be reconsidered for makerspace contexts - assessment should be geared towards growth and learning, different from other forms of assessment designed primarily for accountability, ranking, or certifying purposes (Soster, Fuhrmann & Campos, 2020). In interviews with a variety of maker educators in formal and informal learning environments, these teachers agree that formative assessment methods are crucial and useful in tracking their students' progress (Chan, 2020). When using formative assessment methods, teachers are able to determine concepts and skills students have learned for application beyond the classroom, as opposed to summative assessments / traditional test-scoring (National Research Council, 2014; Hadad et al., 2020). For example, creative modes of formative assessment that teachers have experimented with include creating an online gallery of photographs on Cluster (a private photo-sharing mobile application), posting photographs and videos publicly on Twitter but assessing students individually using personally-created rubrics, or doing a wordcloud class reflection with peer feedback (Chan, 2020).

Problem Statement

During my pre-dissertation (pre-COVID-19) study, I conducted interviews with 24 maker educators in the United States to gather their perspectives and practices in the makerspaces they facilitate. I discovered that the current landscape for assessment in makerspaces varies widely (Chan, 2020); my findings aligned with those of other scholars' of assessment in interdisciplinary STEM education (Brennan et al., 2020). Maker education in some formal environments - schools - fall under a particular core curricular subject, and the school mandates summative assessment for the subject (i.e. the teacher must provide a grade for the student at the end of the semester). Other schools provide teachers with more agency on assessment, or implement maker education as a class period or elective on its own, therefore teachers are not necessarily bound to the rigidity of providing a grade. Some teachers opt to use self-designed or adapted rubrics from resources in maker education networks, or use portfolios (stemming from art education) to track students' work. Some teachers choose not to use any assessment methods, because maker education is a non-examinable subject or elective at their schools.

In informal learning environments, some librarians and facilitators at afterschool makerspaces experiment with media (mainly photographs and videos) for documentation of students' projects. In several instances, this documentation is used as evidence for program evaluation purposes, but minimally used for student learning.

From these interviews, it was evident to me that assessment, whether formative or summative, was highly teacher-driven. Maker educators generally agreed that formative assessment methods are more useful in documenting the process of students' progress (Chan, 2020), but they recognize that students need to consider formative assessment as helpful to their own learning as well, in order for any formative assessment method to be useful overall. Collaboration and communication during formative assessment is a process that education researchers have found to help with positive outcomes in reflection and self-directed learning (Fraile et al., 2017; Panadero & Pardo, 2017; Blau and Shamir-Inbal, 2017; Meer & Chapman, 2015).

Assessing students' work in a process-oriented manner is vital to building a culture of sharing challenges and successes in maker education (Bergner et al., 2019). Research in this area should provide additional insight into how maker educators can support and scaffold maker processes to maximize student agency in their own projects, and to build practices for documenting learning in these complex and dynamic spaces. To address this issue, I have designed a software-aided process to facilitate formative assessment processes, namely documentation and organization of artifacts, between the maker educator and student. This is prototyped as a tool named the *CoCreator App*.

Rationale & Significance

The rationale for this study emanates from the need to find ways to help students in the upper elementary school age range learn productively in interdisciplinary, open-ended maker projects, while also equipping the maker educators with insights and data about how their students are learning. My pre-dissertation interviews with 20+ maker educators have indicated that traditional systems of score-based assessment minimally meet the goal of helping students to understand their processes and be drivers of their own learning journeys. In the United States, multiple nation-wide standards have emerged, such as Next Generation Science Standards (NGSS), the International Society for Technology in Education (ISTE) Standards and the CS4All Framework, to provide guiding benchmarks for maker educators who teach in interdisciplinary settings, but it is challenging to design specific guidelines on assessment metrics for maker education due to the wide spectrum of topics and activities conducted (DeBarger et al., 2013). Although there has been a surge of implementation of maker curricula across schools and informal learning environments globally, along with frameworks to facilitate maker pedagogy, teachers still find it challenging to implement authentic assessments that can capture students' reflection and documentation. My research seeks to illustrate how we can leverage technology as we innovate on facilitating assessment for learning in makerspaces, in theory and in practice.

Statement of Purpose & Research Questions

This is a design-based research study, whereby the mobile application tool *CoCreator App* is designed for maker educators and their elementary school students' assessment and progress-tracking needs in a makerspace. The purpose of this design-based study is to investigate the relationship between the theories of Constructionism and Metacognition in maker education, in Singapore's context. More specifically, I investigate how the CoCreator App's features facilitate documentation and reorganization of artifacts that are personally meaningful and domain-specific to students, and how teachers and students collaborate to improve and iterate on the students' projects based on feedback. Below are the research questions addressed in this dissertation:

1. How might artifact documentation and organization, as a mode of formative assessment, provide new insights to students and teachers in complex making/construction processes?
2. How could artifact documentation embedded in a collaborative tool contribute to students' identification and reflection of new knowledge gained during their making process?

Research approach

With approval from the University's Institutional Review Board, I have studied three implementations of the CoCreator App - one in an elementary school's makerspace during formal curriculum time for Mathematics, one in an informal after-school makerspace, and one in a different elementary school's makerspace during formal curriculum time for Art and Music. Both research sites are based in Singapore, an urban city-state in Southeast Asia. At each of the research sites, I worked with at least one maker educator and their upper elementary school students[2]. As this is a design-based research study, there are altogether three phases of user-testing and data collection with upper elementary to lower middle school students, each time with improvements made to the CoCreator App from the last round of user-testing. Improvements to the CoCreator App test how the addition, modification or deletion of certain features alters how students represent their making processes, reflect on challenges/successes, and communicate their process to the teacher, as well as how these changes support the teachers in gaining an understanding of students' evolving knowledge to enable teachers to provide useful feedback to students. Understanding the relationship between the student, teacher, and tool interactions should provide insight into how we can build tools to support personally meaningful

[2] In Singapore, upper elementary (upper primary) school consists of Primary 4, 5 and 6, equivalent to Grades 4, 5 and 6. Students are approximately 9 to 12 years old.

construction (constructionism) as well as encourage thoughtful reflection during the long (and sometimes chaotic) maker process. As is typical in design-based research, each successive iteration of the tool is compared to the previous iteration, keeping in mind the unique setting and context of each.

To collect qualitative data, the main data collection methods were: video-recorded field observations, video recordings of students using the CoCreator App interface, and audio-recorded semi-structured interviews. I conducted field observations at the research sites to document the interactions that students and maker educators have with the CoCreator App, both individually or together.

Chapter 2. Literature Review

The purpose of this research study is to explore the implementation of a software-aided formative assessment process between maker educators and their students, developed using theories of Constructionism and Metacognition. This literature review was ongoing throughout the prototype design, data collection and data analysis stages of the study. This literature review draws on three main areas: a) formative assessment and metacognition, b) authentic assessment in Constructionist environments, and c) process-oriented documentation for learning. A review of the literature on formative assessment and its relation to the development of metacognitive strategies provides an understanding of the context of assessment practices used in K-12 makerspaces.

Models of Learning: Cognitivism and Constructivism

For the scope of this study on formative assessment in K-12 makerspaces, I apply the cognitivist and constructivist models of learning. The cognitivist learning model emphasizes that knowledge acquisition and internal mental structures lie closer to the rationalist end of the epistemology continuum (Bower & Hilgard, 1981), and that learning has distinct changes between knowledge states (Ertmer & Newby, 2013). Cognitivists claim that learning is concerned with what learners know and how they acquire this knowledge, rather than what learners do (Jonassen, 1991b). Cognitive theories underscore making knowledge meaningful, so that instruction helps learners relate new information to their existing mental structures (schema). When applied to pedagogical practices, the cognitivist model implies that the teacher should recognize that individuals bring different learning experiences to the scenario that can impact learning outcomes, determine the most effective manner to organize new information to build on learners' existing knowledge, and structure practice with feedback to assimilate new information within learners' mental models (Stepich & Newby, 1988). When applied to the K-12 makerspace setting and formative assessments in makerspaces, maker educators would facilitate learning by ensuring that students build on their past knowledge, experiences and skills, by keeping track with students' individual progress, and by prompting students to encourage or redirect them when necessary.

I also draw my model of learning from the constructivist school of thought. The constructivist model extends the cognitivist model by centering the learner's personal experiences with the world, and claims that the individual creates meaning from their own experiences (Jonassen, 1991b; Bednar, Cunningham, Duffy & Perry, 1991). The constructivist model states that transfer is facilitated by learners' involvement in authentic tasks anchored in meaningful contexts - the authenticity and context of the experience are critical to the individual's ability to use ideas to create knowledge (Ertmer & Newby, 2013). The teacher facilitates and guides students through documenting and organizing artifacts, but the student ultimately constructs knowledge that is authentic to their personal experience. More tangibly, prior empirical studies in formative assessment and metacognition expand on these cognitivist and constructivist models of learning that have framed my perspective of maker education and laid the groundwork for the CoCreator App's features.

My research leverages key features of these models of learning - that knowledge is constructed through individual experiences in their environments (constructivist) and that knowledge is constructed through rational internal processes and connections (cognitivist) - to apply both to the context of learning in makerspaces. In a makerspace, students construct knowledge through tinkering with materials, experimenting with hardware and software tools, and iterating on their projects (constructivist). Students also construct knowledge through reflecting on their successes and challenges, asking their teachers or peers questions for guidance or assistance, and overcoming their challenges by testing new ideas and solutions (cognitivist). These complex physical and mental processes overlap and intertwine, thus there is a need to facilitate these learning processes explicitly so that students externalize their rational thought (aligning with Metacognition) and share with their peers to learn (aligning with Constructionism); on the teachers' end, this generates a need to keep track of students' progress to guide them effectively (aligning with assessment for learning).

Formative Assessment & Metacognition

There are three pillars of educational assessment - formative, summative and program evaluation (Pellegrino, 2018). Formative assessment comprises teachers providing timely feedback to students about their progress through different means - homework, observations, computer-assisted technologies, conversations - and using various methods to inform day-to-day and month-to-month decisions about instruction (Black & Wiliam, 1998; Wiliam, 2007; Pellegrino, 2018). On the other hand, summative assessment involves determining student achievement or attainment of a predefined level of competency after completing a phase of education (Pellegrino, 2018), while program evaluation focuses on helping administrators and policymakers judge the effectiveness and quality of educational programs and institutions (Pellegrino, 2018). As my model of learning necessitates that students formulate their own rational mental models and publicly share their work with peers to learn, formative assessment practices are best-positioned to provide insights on students' learning. Hence, this literature review focuses on the development of authentic and creative modes of formative assessment for learning in makerspaces.

Another learning theory that is equally vital to this research study is metacognition. Flavell states: “Metacognition refers to one's knowledge concerning one's own cognitive processes or anything related to them, e.g., the learning-relevant properties of information or data. ... Metacognition has to do with the active monitoring and regulation of cognitive processes” (1976; Flavell, Miller & Miller, 1985). Metacognition can occur before, during or after a learner engages in a cognitive task (Winne & Azevedo, 2014). I have chosen to focus on metacognition that occurs *during* students’ engagement in their maker project (in the context of a makerspace environment), in order to scaffold the process of creating an authentic mode of assessment for themselves. Furthermore, cognitive psychologists discern between three forms of knowledge - declarative knowledge - beliefs about self-efficacy (Muis & Duffy, 2012; Bandura, 2001), task understanding (Greene, Hutchison, Costa, & Crompton, 2012), learning strategies (Jacobs & Paris, 1987); procedural knowledge - the process of carrying out cognitive work to accomplish tasks (Winne & Azevedo, 2014); and conditional knowledge - the ability to identify if-then circumstances to determine if a procedure is suitable to approach a goal (Winne & Azevedo, 2014). These are all forms of metacognitive knowledge that will surface through students’ maker journeys; I will return to these concepts later while discussing the implementation of scaffolds in the CoCreator App’s design.

Authentic Assessment in K-12 Makerspaces. Assessing learning in interdisciplinary, project-based learning environments such as K-12 makerspaces has been challenging with traditional classroom measures of achievements such as grades and tests. In fact, some of these traditional quantitative measurements could be perceived as antithetical to the nature of Constructionist learning in makerspaces (National Research Council, 2009). Authentic assessment has been introduced to this discussion on creating more personalized assessment methods. Frey (2018) explains "authentic assessment" as methods that present real-world scenarios, where students "integrate and apply what they have learned through contextualized tasks" with the goal of indicating the degree to which students understand and apply what they learned in a meaningful way. For an assessment to be authentic, it should portray the context of the assessment, student role and clear scoring criteria (Frey, Schmitt & Allen, 2012). This list of characteristics of authentic assessments will resurface in the technology design for the CoCreator App.

Over the past few years, maker educators have increasingly used authentic assessment methods in formal and informal learning environments to measure students' learning outcomes in STEAM (Science, Technology, Engineering, Art & Mathematics) (Carter, 2013; National Research Council; 2009; Chan & Holbert, 2020). Most recently, Brennan and colleagues published a compilation of authentic assessments that teachers use to assess creativity in K-12 computing education in their local contexts (2020). This collection included a selection of 50 authentic assessment formats, from different types of portfolios, rubrics, checklists, to presentations. Oftentimes, teachers also used more than one type of authentic assessment in the course of their classes to gather a variety of perspectives and data points about student growth and progress. teachers sought to understand what is creative for their individual students, and supported them by incorporating feedback from multiple sources - peers, family, self assessment

- so that these become scaffolded opportunities for students to develop judgment on their work (Brennan et al., 2020).

Process-Oriented Documentation for Learning. Evidence-centered design calls for process-oriented documentation when tracking learning and progress in maker projects. The process of making is immersive and often exploratory, thus we need to acknowledge that the pedagogy and assessment of making affords multiple pathways to completion (Kim et al., 2020). Maker activities sometimes also include large amounts of collaboration between different parties (Clapp et al., 2016), so individual contribution and competency evaluation may be blurred (Murai et al., 2020). Finally, maker projects are often inter and trans-disciplinary, thus there may be challenges isolating particular skills or knowledge to assess. Moreover, holistic skills such as risk-taking and problem-solving typically occur in makerspace contexts, but there is currently no satisfactory method to measure those skills (Duckworth & Yeager, 2015). Due to these reasons stated above, process documentation is vital to serve as evidence on capturing learning in these areas that are challenging to measure with conventional assessment methods.

From interviews that various scholars have conducted with maker educators primarily based in the United States, these maker educators consistently mention documentation tools - such as portfolios, journals, diaries, social media, blogs, surveys - allow students to communicate their process of making and hence their learning from the process, rather than only the final product (Murai et al., 2020; Brennan et al., 2020; Chan & Holbert, 2020). Some maker educators state that these documentation tools help provide data so that they can give students constructive personalized feedback, while some state that documentation helps students develop stronger independent metacognitive strategies, as students tend to be more reflective and aware of their learning styles (Murai et al., 2020). As illustrated, maker educators' assessment practices vary, since there is no established strategy that fits all contexts. Rather, assessment practices in makerspaces are situated in context and dependent on the stakeholders. The next subsection reviews different types of formative assessment methods that highlight process documentation.

Types of Formative Assessment. Portfolios and rubrics are two main types of formative assessment methods currently used in K-12 making contexts.

Portfolios. Portfolios originally stemmed from art education, since art has traditionally been a subjective area to assess to begin with (Gardner, 1989). Portfolios are commonly employed to collect, organize, and review artifacts created by learners (Dorn, Madeja, & Sabol, 2004) - this can be done in a hard copy, such as keeping a design journal or scrapbook (Murai et al., 2020), or digitally (Chang, Keune, Peppler, Maltese & Regalla, 2015) in an electronic portfolio using currently available mobile and web applications such as Seesaw, Weebly, Wix etc. Portfolios are useful in providing opportunities to demonstrate students' creative processes, because portfolios can illustrate topics and skills that students have learned, how they question, analyze, synthesize, solve problems, and create new ideas, or how they design and build prototypes (Doppelt, 2009). Portfolios also show how students interact intellectually, emotionally and socially with others (Collins, 1991; Wolf, 1989).

However, for elementary school-aged students, maker educators may have to play a bigger role in encouraging and reminding students to capture photographs and videos for their portfolios to make sure that they collect evidence of works-in-progress (Chan & Holbert, 2019). Because this might take students out of their flow of making, it is sometimes challenging to capture meaningful evidence in the moment of making (Murai et al., 2020). Fostering a broader maker classroom practice to increase students' agency and ownership of their portfolios takes time, and requires input from both students and maker educators.

Research studies have demonstrated that the use of electronic portfolios (e-portfolios) has helped students gain significant improvement in acquiring content knowledge and metacognitive strategies (Meyer, Abrami, Wade, Aslan & Deault, 2010; Schroff, Deneen & Ng, 2011). Meyer and colleagues discovered that fourth to sixth-grade students who used ePEARL, an e-portfolio tool, in medium to high-implementation classrooms showed significant improvement in self-regulation skills that students self-reported (2010). Another study examined students' behavioral intentions (perceived usefulness, perceived ease of use, attitudes towards usage) to use an e-portfolio system (Shroff et al., 2011). These scholars developed an e-portfolio usage questionnaire from existing instruments and scales related to the technology acceptance model (Davis, 1989; Davis, Bagozzi & Warshaw, 1989). The results showed that perceived ease of use had a significant influence on perceived usefulness, which means that students are more likely to adopt an e-portfolio system when they find the technology useful. Conversely, there was no significant relationship between perceived usefulness, attitude towards usage, and behavioural intention, suggesting that students may still use a technology even though they do not have an entirely positive experience with it, so long as the technology is considered useful (Shroff et al., 2011). Connecting the findings of Shroff and colleagues' study to my discussion on how portfolios could be helpful as assessment tools in makerspace contexts, it would be important for maker educators to foster an environment or culture where students recognize intrinsically that keeping a portfolio is useful and authentic to their maker projects. If portfolios do not come across as useful or easy to use, then students' back-and-forth transition between their flow of making and portfolio documentation may become frustrating.

Rubrics. Rubrics are widely used as an assessment tool in makerspaces. Using rubrics can increase learning and performance under formative assessment conditions, for example by enhancing metacognitive strategies such as self-regulated learning (Panadero & Jonsson, 2013). Such learning gains could also emerge from instructional purposes, such as teachers communicating their expectations for an assignment through a rubric, providing more detailed feedback on works-in-progress or final products with higher reliability (Andrade, 2000; Moskal, 2003). Scholars have discussed that assessment criteria should be introduced before task execution begins by presenting a rubric to students, so that students can monitor and evaluate themselves accordingly during the course of the task (Andrade & Brookhart, 2016; Panadero & Alonso-Tapia, 2013). Nevertheless, while providing criteria (or a rubric) does not guarantee strategic use from the get-go, self-regulation is more likely to occur when rubrics are provided (Lan, 1998).

However, as stated in one of Brennan and colleagues' case studies, a teacher observed that assessing creative interdisciplinary work using objective rubrics could impose inauthentic limits on students' imagination when students constrain themselves and conform to the rubrics that their teacher had set for them (2020). In the spirit of allowing students to take the driver seat in authentic formative assessment, formative assessment between the teacher and student is a path that should be more extensively explored, particularly in a makerspace environment. Fraile and colleagues (2017) studied the effects of co-creating rubrics against only using rubrics in an undergraduate sports sciences degree program. The study had mixed results, finding that students who co-created the rubrics had higher levels of learning self-regulation measured through think-aloud protocols, whereas there were insignificant differences from the self-reported self-regulation and self-efficacy questionnaires. Thus the scholars concluded that co-creating rubrics may influence students' activation of metacognitive strategies (Fraile, Panadero & Pardo, 2017). Blau and Shamir-Inbal studied co-creation of course content and learning outcomes by students in a graduate school of education. They cited that this technology-enhanced embedded assessment platform they implemented, combined with individual reflection and co-creation of course content and learning outcomes, helped students develop self-regulation and co-regulation metacognitive skills (Blau and Shamir-Inbal, 2017).

In these examples, students were instrumental in creating the standards and scaffolds in the rubrics, prompting them to reflect on their expected performance and skills as they progress through a project. Maker educators generally already use rubrics that they develop, or rubrics from state-wide or nation-wide frameworks. Although rubrics will not be the focus of my dissertation study in the CoCreator App, insights into how rubrics are constructed with and by students are relevant. The CoCreator App aims to emulate scaffolds such as providing reflection prompts in weekly posts, and practices where students are involved in creating methods for organizing their artifacts.

Chapter 3. Research Methodology

The purpose of this design-based research study is to explore elementary school students' and teachers' use of the CoCreator App, a mobile application that facilitates collaboration between maker educators and elementary school students when documenting learning in makerspaces. The CoCreator App enables students to document processes such as brainstorming, prototyping individually and/or in a group, and constructing artifacts in a makerspace. In the makerspace, we can expect students to also be engaged in discussions with groupmates, peer-to-peer feedback, teacher-student interactions and feedback, and reflections. The CoCreator App also allows teachers and mentors to check in on students' progress, identify points of discussion and areas of improvement for students in their work, and provide feedback and comments asynchronously on the application.

For data collection, I employed criterion-based sampling for my research sites and participants to ensure that all my research participants represent those who have experienced a similar phenomenon of teaching and learning in a makerspace for at least a couple of years.

Research Sample

Sampling Strategy. Using criterion-based sampling, I have defined three main criteria for selecting my research sites, listed below:

- There is a fully functioning makerspace at the research site;
- This makerspace serves upper elementary school students;
- This makerspace implements STEAM, project-based curricula. The category "STEAM" comprises many types of activities - this could entail interdisciplinary hands-on projects that involve physical computing, creative technologies, basic electronics, robotics, or

computer programming. Students usually work on these projects over an extended period of time, between a full day to a few weeks.

As much of previous scholars' research focused on middle and high school students in the K-12 space, I chose to work with upper elementary school students to explore challenges and behaviors of younger students when engaging with formative assessment. Furthermore, as Singapore's Ministry of Education focuses on expanding interdisciplinary maker education in all elementary schools across the nation, I hope that my research elucidates areas of growth for formative assessment in maker education at the elementary school level. At least one site will be a formal learning environment, and one site will be an informal learning environment. For my research participants, I have listed the following criteria:

- The maker educators or mentors have at least two years of experience teaching in makerspaces or in a project-based, high-tech learning environment. This specification ensures that the teacher / mentor participants are not brand new to maker education, and have had some experience leading a maker education class or program, facilitating group projects with students, mentoring students, and providing feedback to students.
- The maker educators or mentors are willing to communicate regularly with me to schedule data collection periods, provide feedback on features of the CoCreator App.
- The upper elementary school students are familiar with the makerspace they are working in, and have had some previous experience learning and working in a makerspace.

Research Site & Participants. There were 3 phases of data collection, and I used different sites and participants for each phase. Phase 1 was considered a preliminary phase of data collection and it occurred during the peak of the COVID-19 pandemic, thus I recruited individual Singaporean and American children between the ages of 8 to 13 and conducted online interviews with them about formative assessment in maker education. This was convenient sampling as I relied on my direct network at Columbia University and at home in Singapore. Findings from Phase 1 contributed to development of the CoCreator App prototype that was implemented in Phase 2. Phase 1 was completed from August to September 2020.

For Phase 2, I selected two research sites - a co-ed public elementary school and a co-ed after-school makerspace, both located in Singapore. I chose a formal and an informal learning environment, as I was interested in studying the similarities and differences that may emerge in students' and teachers' workflows and interactions in relation to the CoCreator App in these learning environments. Similarly, findings from Phase 2 contributed to an improved version of the CoCreator App. Phase 2 took place from November 2020 to January 2021.

For Phase 3, the research site I selected was an all-boys' public elementary school in Singapore where students come from various socioeconomic backgrounds. Although there is a limitation on gender diversity as this school only serves male students, I chose this site because it is a designated zonal lead maker education school in Singapore, and has formally incorporated elements of maker education into core curricular subjects. It is important to my study that this site, a formal learning environment, has clear learning objectives from core curriculum in its maker education program, which my school site in Phase 2 did not. At this site, I worked with the upper elementary students. Two maker educators participated in my research - a senior Art teacher, and a junior Music teacher. They are both highly experienced and passionate about developing their school's makerspace. The senior teacher has had 20+ years of teaching experience in her core subject area Art, while the junior teacher has had 5+ years of teaching experience in Music and creative technologies. For my study, I specifically worked with teachers and mentors who facilitated longer-term programs that are at least a month long, so that the students and teachers could work with the CoCreator App over an extended period of time. I also recruited children participants who are around 10-12 years of age (upper elementary grade levels), to keep the age range of students I work with consistent with those in previous data collection phases. Phase 3 occurred from August to October 2021.

Research Design & Methodology

This research design is based on theoretical grounding from Chapter 2's literature review, where ongoing and relevant research is continuously updated. The conceptual framework developed from the literature review has guided the development of data analysis, interpretation, and synthesis phases of the research. The following sub-section, Data Collection Methods, will elaborate on the methods and processes I used. Between the data collection phases, feedback was recorded from both students and maker educators through field observations and interviews to incorporate into the CoCreator App. I conducted field observations and interviews at each implementation. The implementations were compared based on students' and teachers' styles of engagement and interaction during the artifact documentation process, for example through the frequency of use of particular features of the CoCreator App, the language they use to generate ideas, collaborate or explain their opinions and feedback. Tables 1, 2, and 3 below map the maker education program structures for Phases 1, 2, and 3 respectively.

Table 1 *Program Structure for Phase 1*

Venue	Session	Topic	Activity	Artifacts Used / Collected
Online Video Conference / At Home	#1	Brainstorming & Building	● Students discuss plans for documentation ● Students start building a model house out of recycled materials ● Students execute their plan for documentation during making	Notes on CoCreator App: Preliminary Prototype

Table 2 *Program Structure for Phase 2*

Venue	Session	Topic	Activity	Artifacts Used / Collected
School Makerspace	#1	Brainstorming	● The teacher introduces the students to bridges ● The teacher introduces the students to the CoCreator App ● Students form project groups ● Students sketch bridge designs	Sketches on paper Notes on CoCreator App
	#2	Bridge Design	● Continue sketching bridge designs ● Consolidate ideas with teammates	Sketches on paper Notes on CoCreator App
	#3	First "Build Day"	● Collect recycled materials to use for building ● Build bridges	
	#4	Editing Bridge Design	● Test the strength of the bridges ● Reflect on different teams' designs ● Edit designs of original bridges	Sketches on paper
	#5	Second	● Build bridges with edited	

		“Build Day”	designs	
	#6		• Test the strength of the new bridges • Reflect what made students’ second bridges stronger than their first bridges	Text reflections on paper
Informal Afterschool Makerspace	#1	Planning	• Students discuss ideas and plans with their individual mentors	CoCreator App; Text messages on Slack
	#2	Planning	• Students continue discussing ideas and plans with their individual mentors • Some students start user interviews, or do online research about the prototypes they would like to build	CoCreator App; Text messages on Slack
	#3	Gather Materials	• Students compile a bill of materials. Mentors assess whether the project is feasible in the time frame of the program, and assist in sourcing the materials	
	#4	Prototype / Test	• Students start building their first prototype out of recycled materials • With their mentors, students evaluate if changes need to be made	CoCreator App; Photographs; Text messages on Slack
	#5	Prototype / Test	• Students continue building their prototype • Mentors introduce the students to industry experts, and students go through their ideas and prototypes with these industry experts	CoCreator App; Photographs; Text messages on Slack

	#6	Prototype / Test	● Students continue building their prototype, based on changes and feedback from mentors and industry experts ● Students are encouraged to test with target users too	CoCreator App; Photographs; Text messages on Slack
	#7	Prototype / Test	● Students edit their prototypes based on feedback from mentors and target users ● Students finalize their prototypes and brainstorm how they would like to showcase their prototypes at Demo Day	CoCreator App; Photographs; Text messages on Slack
	#8	Demo Day	● Students showcase their projects to the makerspace's community members, their families, and the public	Photographs

Table 3 *Program Structure for Phase 3*

Venue	Session	Topic	Activity	Artifacts Used / Collected
School Makerspace	#1	Introduction to Design Thinking and the Design Process	● Learn about the stages of design thinking and how to apply to maker projects	Photographs; Text reflections; Self-reported confidence level
	#2	Introduction to Scratch and the Makey Makey	● Learn a few Singaporean folk songs (these will be coded on Scratch later) ● Review concepts learnt previously on Scratch ● Familiarize with the Makey Makey microcontroller, and about the concept of closed circuits to ensure that the Makey Makey is connected properly to conductive	

			materials and to Scratch	scores on the CoCreator App
	#3	Interviewing	● Form groups ● Interview target user ● Consolidate the target user's preferences	
	#4	Building the "internal" electronics	● Program the group's folksong choice on Scratch ● Assemble the Makey Makey to play the coded song	
	#5	Building the exterior design	● Build the project using recycled and art materials available in the makerspace	
	#6	Demo Day	(canceled due to COVID-19 school closure)	

Data Collection Methods.

Field Observations. I used my research questions as the framework to develop an observation guide (in Appendix A). These field observations were conducted online in Phase 1 due to COVID-19 constraints, and onsite at the research sites for Phases 2 and 3. I observed how the students use the CoCreator App to generate artifacts, hashtags[3] and reflections for their projects. In Phases 2 and 3 when teachers and mentors were involved, I also observed how the maker educator interacts using the CoCreator App with their class of students, who may all have different projects.

Developing the Interview Protocol. I used my research questions as the framework to develop an interview protocol that was administered to students and maker educators

[3] Hashtags are words or short phrases written with a # symbol at the front (for example: #coding) to denote a keyword or topic. In this case, students can use hashtags to categorize the photographs they take of their work on the CoCreator App, potentially to review at a later date, or to remind themselves about the specific lesson or activity.

individually (refer to Appendices B to F for the interview protocols used in Phases 1, 2, and 3). I interviewed students at the end of the maker program, and the teachers two-thirds into the maker program. This interview protocol focused on participants' experiences and opinions on documenting and organizing artifacts. The protocol included additional prompts on how the student and maker educator used certain features of the interface to find out whether and how these features contributed to students' metacognitive development.

Interviews with maker educators and Students. During my observation sessions that lasted over eight weeks, I made a note of the students I observed, so that I could interview them later. I prioritized interviewing the students whom I have observed multiple times, particularly students who were self-selected to be the "documentation leader" for their group. For students, I received prior parental consent, and interviewed them over an online conference call (the Singapore Ministry of Education requested that the interview took place through a conference call). For maker educators, I sent an individual email to schedule an interview time - this was conducted via Zoom as it worked logistically better for them. Before the interview commences, the maker educators signed a consent form and the students signed an assent form - these forms are required for participation. All interviews were audio-recorded in their entirety. On completion of the interview, I transcribed the audio files verbatim.

Data Analysis Methods.

Qualitative Thematic Analysis. I primarily used thematic analysis to code the qualitative data that I collected from interviews and observations. Fereday and Muir-Cochrane (2006) describe thematic analysis as "a search for themes that emerge as being important to the description of the phenomenon," and Braun and Clarke (2006) describe it as "identifying and encoding patterns of meaning in primary qualitative research." I chose thematic analysis as it provided flexibility in my approach to discover emerging themes and patterns in the data. I followed Swain's (2018) practical approach to thematic analysis, where he proposes three main stages - 1) developing a priori codes, 2) creating a posteriori codes while coding, 3) collapsing a priori and a posteriori codes into family codes once I complete a pass. I created a priori codes based on my research questions, objectives, interview questions, and observation guide. These a priori codes largely centered around students' interaction with peers and with the maker educator regarding documentation and feedback, and use of the CoCreator App's features. I constructed a coding scheme on a spreadsheet to track my a priori codes and definitions.

Then, I gathered a group of 4 additional research assistants from my research group to code the interviews and observations with me, and I calculated the inter-reliability rater (IRR) score. At first, our IRR score was ~60% - the discrepancies in interpretation laid in the codes related to *Group Dynamics* and *Collaboration*. We discussed adding new sub-codes, such as "Group dynamics when documenting" and "Group dynamics when not documenting, and "Student Roles" and Exchanging Ideas" under *Collaboration*. As we did another pass on a couple of transcripts, we added new codes, such as *Lack of agency*, *Elaboration*, *Resolving Conflict*, as we noticed that these instances appeared multiple times and may lead to interesting insights about how students behaved in different groupwork circumstances.

These research assistants and I added new a posteriori codes to the coding scheme as we continued reviewing transcripts from Phase 3 of data collection. Although we primarily coded interview transcripts, we also reviewed content of students' posts / photographs, text captions and reflections that students wrote, and any other artifacts that students created and used during their documentation process (such as hardcopy or softcopy notes, sketches, etc.). The coding scheme had three main families of codes: feedback; documentation practices; CoCreator App features (refer to Appendix G). These code families were created to relate directly to the research questions, and I investigated contrasts between codes for Phases 2 and 3, as well as overlaps between these code families.

Example of Qualitative Data Analysis. Below is an illustration of the process where I analyzed my interview transcripts and field notes related to feedback between students and teachers in a makerspace during Phase 3 of data collection. My aim was to investigate both synchronous in-person feedback and asynchronous feedback on the CoCreator App as formative assessment, using qualitative data from a mix of artifacts and observations. I examined students' updates on the CoCreator App to study the content of the photographs they took in class, written comments, hashtags they chose to categorize their photographs, and how they self-reported their confidence levels. I also looked at the teachers' interface of the CoCreator App to study how they asynchronously responded to students' updates. I then triangulated this data with video-recorded observations of teachers in the process of providing students with feedback synchronously in class, and coded for instances where feedback was classified as task, process, self-regulation, of self/praise (Hattie & Timperly, 2007), according to the codes established in my coding scheme. Preliminary findings demonstrated that teachers mostly used the CoCreator App to check students' work briefly and provide simple feedback, leaving more detailed feedback for synchronous time in class. Teachers were more inclined towards synchronous feedback when a synchronous mode is available, because they are able to quickly gauge students' understanding through their response and reaction to the feedback.

Chapter 4: First Implementation of the CoCreator App

The purpose of this dissertation is to explore a technology-enhanced formative assessment process based on documentation and feedback at an upper elementary school level, using the theories of Constructionism and Metacognition to drive the design and implementation. The CoCreator App was built to facilitate formative assessment in the maker learning environment. Relating to my research questions, my goal is to discover how students and teachers gain new insights when students engage in their maker projects, and to identify instances of collaborative learning between students and teachers that help students achieve productive reflections.

This chapter presents key findings from my first two phases of implementation - Phases 1 and 2. Phase 1 is the implementation of the preliminary low-fidelity prototype of the CoCreator App, and involved online interviews and observation sessions with 15 students (13 elementary school students and 2 middle school students). Phase 2 builds on the findings from Phase 1 and is the implementation of the mid-fidelity prototype of the CoCreator App. Phase 2 involved two research sites - a school's makerspace occurring during the students' formal mathematics period, and an informal afterschool makerspace occurring during the students' end-of-year vacation. Twelve elementary school students and one maker educator participated at the formal school site, while eight students (five elementary and three middle school students) and two maker mentors participated at the informal makerspace site. Classroom field notes from observations, interviews, focus groups, and artifacts via the CoCreator App and through other modalities were collected throughout the course of the dissertation's two-year implementation in Singapore.

In this chapter, I include three case studies from Phase 1 and two case studies from Phase 2. The cases represent the various methods and perceptions students have regarding documentation for maker projects, their interactions with the CoCreator App, and their communication with their teachers or mentors regarding feedback to advance their understanding of new concepts and skills they may learn through their maker projects. All student names presented in the findings are pseudonyms; real names have been omitted. These cases address my research questions on exploring how 1) documentation provides new insights to students and teachers about their making processes, and 2) students identify and reflect on new knowledge gained via documentation.

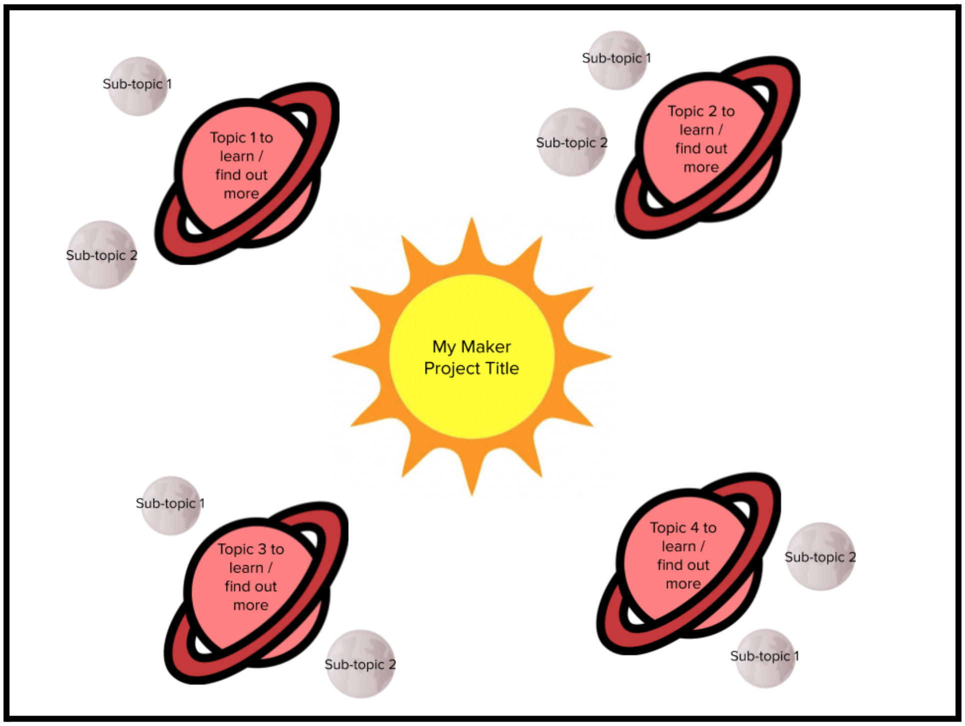
Phase 1

Conception

Based on a pre-dissertation interview study I had conducted with K-12 maker educators around the United States, I gathered that both a priority and a challenge for maker educators lies in engaging their students actively in the assessment process of a long-term maker project (Chan, 2020). Students often work and learn at different paces, and maker educators often develop their own checklists or rubrics to provide feedback "on the go" as students iterate on their projects. However, maker educators felt that students were generally not actively involved in assessing themselves and their own progress, making it a one-sided attempt for maker educators to track students' progress. While students are learning new skills and completing tasks at each step of their making process, it is essential that students reflect continuously on their progress. From a constructivist perspective, reflection is a vital component of assimilation. From a constructionist perspective, a key tenet is sharing with others discoveries from their own projects. Artifact documentation encourages students to reflect continuously during making, and as a result be involved in their own formative assessment process overall. For educators, students' reflections are important because it provides them with a window into how students perceive their own learning. Educators may use students' reflections to compare them with their own assessment of students' work, to identify discrepancies or alignment to help students advance.

My objective for this first preliminary prototype of the CoCreator App was to explore an interface and analogy where students are prompted to actively think about how they would track their own progress in a maker project (before actually beginning the project), and thus engage in pondering about formative assessment methods that they would like to try to use during making. This first phase entailed using a low-fidelity concept map tool with a solar system analogy (Figure 1) to guide students in pre-empting challenges they might face in their maker project, and then in identifying possible methods of documenting their progress.

Figure 1 *Low-fidelity CoCreator App in the form of a concept tool with a solar system analogy (first design iteration)*



Development of the Preliminary Prototype

I chose to use a solar system analogy as part of the tool's design, in order to represent how themes (planets) revolve around the main project idea (Sun) to make the activity more accessible to students who may be unfamiliar with concept maps. The purpose of Phase 1 was three-fold: 1) to understand how students identify ways to document their projects and think about formative assessment, 2) to discover my target students' understanding of the solar system analogy in the concept map tool, and 3) to note down important prompts that a maker educator would need to provide to students while students figure out how best to document their maker project. These are goals set to orient the design of the preliminary CoCreator App prototypes, so that I can figure out designs for artifact documentation and organization later (relating to the dissertation's research questions). I created Phase 1's prototype on Google Draw.

Implementing Phase 1

Phase 1 involved hour-long interviews with 15 students, aged between eight to thirteen years old. Students were physically located in Singapore and in the United States. I recruited half of the students through my personal network at Teachers College, and half of the students through social media announcements about my study. Phase 1 occurred during the COVID-19 lockdown period (happening both in Singapore and in the United States), thus I conducted interviews and observations online through video conferencing. Students were provided with a blank template of the solar system concept map tool and then prompted to build a model house using recycled materials and objects found at home.

For the interview, I used a protocol (Appendix B) that guided students in articulating how they would document the process of building their model house to gather students' perspectives about process documentation. The interviews lasted around 45 minutes to one hour for each student. Five students were interviewed individually, and another ten students were interviewed in pairs, because the student participants included their sibling of a similar age at home. For one group, two students who are friends at school logged into the call to do the interview together. For these group interviews, I also observed how students communicated with one another to discuss their opinions about documentation and formative assessment.

Findings from Phase 1

I coded my interviews and observations of these interviews thematically using a bottom-up approach to identify emergent themes that could guide me in iterating on the tool design for Phase 2. During the interviews, I looked out for language students used in conceptualizing what documentation meant to them, and how it may or may not be useful for the maker project prompt they were presented with. I also observed how students used the CoCreator App prototype, questions they asked about it, and how they discussed any past experiences related to making and documentation. I noted down questions related to documentation, planning and brainstorming that I used to further prompt their reflection. Finally, when the students started making, I observed whether they would use their intended modality of documentation, and if they changed their minds about the modality of documentation during making.

From these interviews and observations, I observed that students used the concept map tool in primarily three different ways, which I categorized as: goal-oriented; challenge-oriented; and top-down procedural visualization.

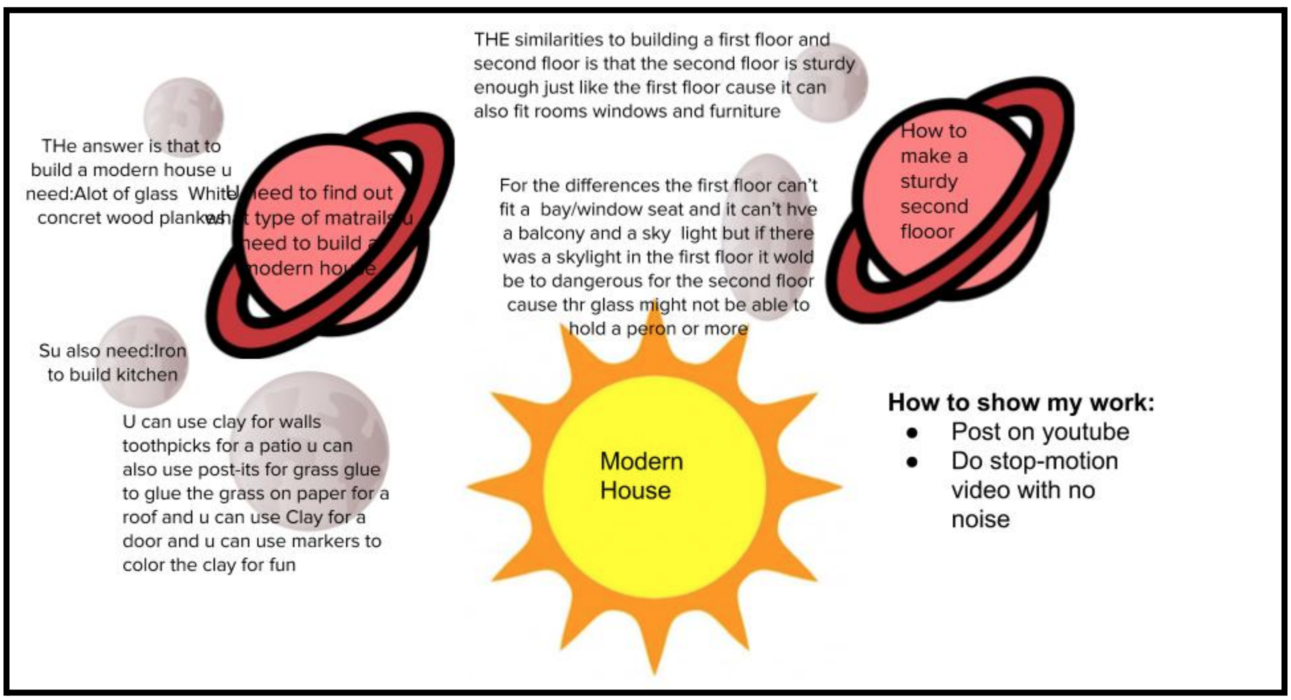
Students who exemplified goal-oriented behavior would indicate major project goals in the planets and explain how they would achieve their goals in the corresponding moons orbiting the planets. For students who pondered more on challenges, they based their considerations for this maker project during the interview on past experiences engaging in maker projects in school or at home. They provided a variety of responses ranging from specific structural challenges that may occur in their prototype (such as “the wall material might not be strong enough”), to mental and emotional challenges (such as “I must tell myself not to give up when things don’t work the way I want it to”). Finally, a subset of students used the concept map tool to visualize top-down how they would execute the procedure of building the house from bigger to smaller sections, i.e. from rooms (“living room”) to specific furniture and characters (“chair” / “pet” / “car”).

Given these three main pathways of approaching the concept map, and as part of the interview protocol, I (the facilitator) would prompt each student with additional questions on documentation, such as “If your friend wanted to follow your model house design, how might you record or jot down all the steps you are taking to build this house?” and “How would you show that you are exploring different types of materials you want to use?”.

When asked how they would show their progress and process, 11 out of the 15 students interviewed would latch onto a particular modality they were already familiar with. For the other 4 who did not choose a modality or took much longer to choose a modality, they were brand new to the concept of documenting and recording in general, and on the younger end of the age range (8 year-old students). One of these younger students had an older sister and participated in the interview and making session with her. This young student would agree to whichever method his older sister chose for both of them, without much consideration or input.

Goal-Oriented Behavior. The CoCreator App helped Hannah plan tasks she needed to complete in order to build her model house (shown in Figure 2 below). However, as for deciding on the modality of documentation, she stated that she would take a video of her entire process focused on her hands and construction of the prototype, because the gist of her making process occurred around her hands. She would then post the video on her YouTube channel, because she had been doing this for her hobby (creating and streaming gaming videos) for over a year. She then stated that perhaps she could create an audio-less stop-motion animation video of her making process, focused on her hands, because stop-motion animation video was a creative medium that she enjoyed, introduced to her earlier during a school project. When further prompted why she would only focus on her hands and not her surroundings or full torso to show her entire self interacting with the prototype she would build, she voiced her discomfort regarding showing her face on YouTube videos because her face would be identifiable. Stemming from her hobby, video was clearly the modality that Hannah preferred that she envisioned would work best for her maker project. She adhered quickly to this decision about using videos as her documentation modality.

Figure 2 *Hannah's concept map, classified as goal-oriented behavior*

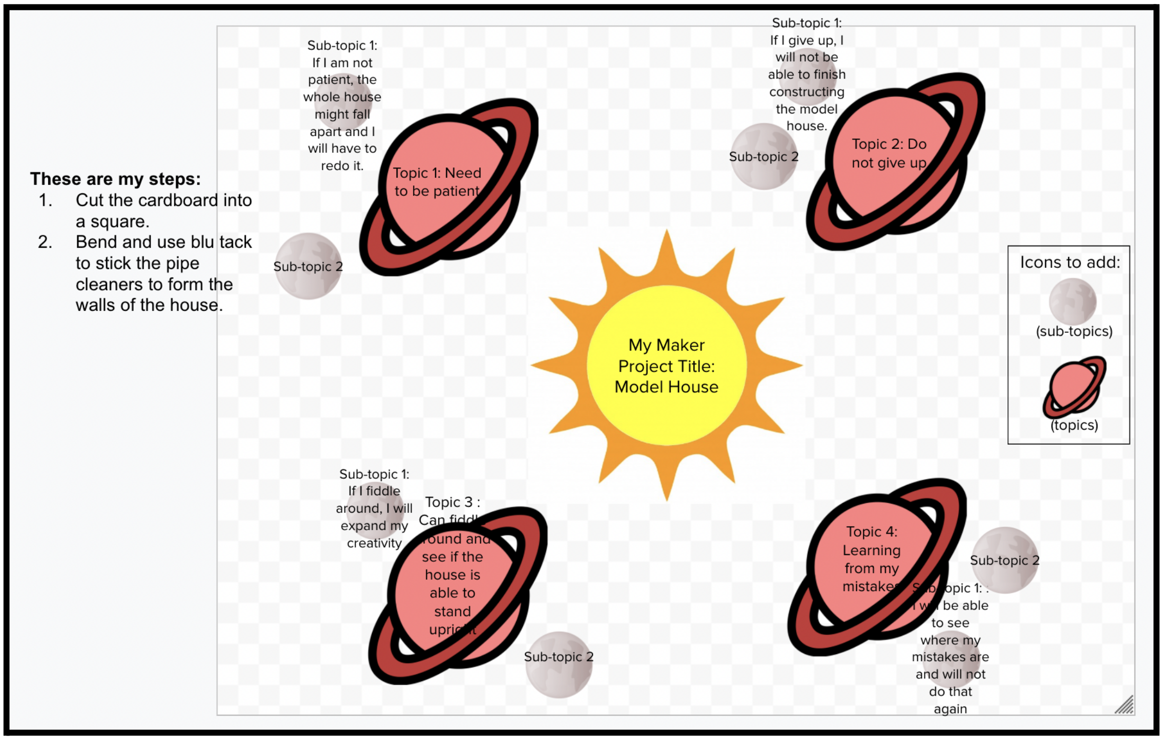


Hannah's concept map is an example that I classified as "goal-oriented" as she clearly stated her main objectives in the red planets: "need to find out what type of (materials you) need to build a modern house" and "how to make a sturdy second (floor)". Then, in and around the grey moons, she wrote answers that relate to the content of her goals in the planets. Although we do not directly observe from the concept map her opinions about documentation and formative assessment, we could interpret that she approaches a new maker project by brainstorming main goals that she needs to achieve to build the product, and that she uses the concept map tool to document her thoughts about her goals. 4 out of the 15 students exhibited this “goal-oriented” behavior.

During making, she set up her smartphone’s camera at the corner of her table focusing on her hands and prototype (as she had planned), but decided that doing a stop-motion animation video would require another person’s assistance because she physically could not take frames / photographs in milliseconds and work on her project simultaneously. This was Hannah’s entire process deciding that she would use a normal smartphone video for documentation.

Challenge-Oriented Behavior. Figure 3 below shows Valerie’s approach to the concept map, which I categorized as “challenge-oriented” as she led with social-emotional challenges related to maker projects. In her planets, she wrote main challenges such as “Need to be patient,” “Do not give up,” “Can fiddle around to see if the house is able to stand upright” and “Learning from my mistakes.” 2 out of 15 students exhibited this “challenge-oriented” behavior.

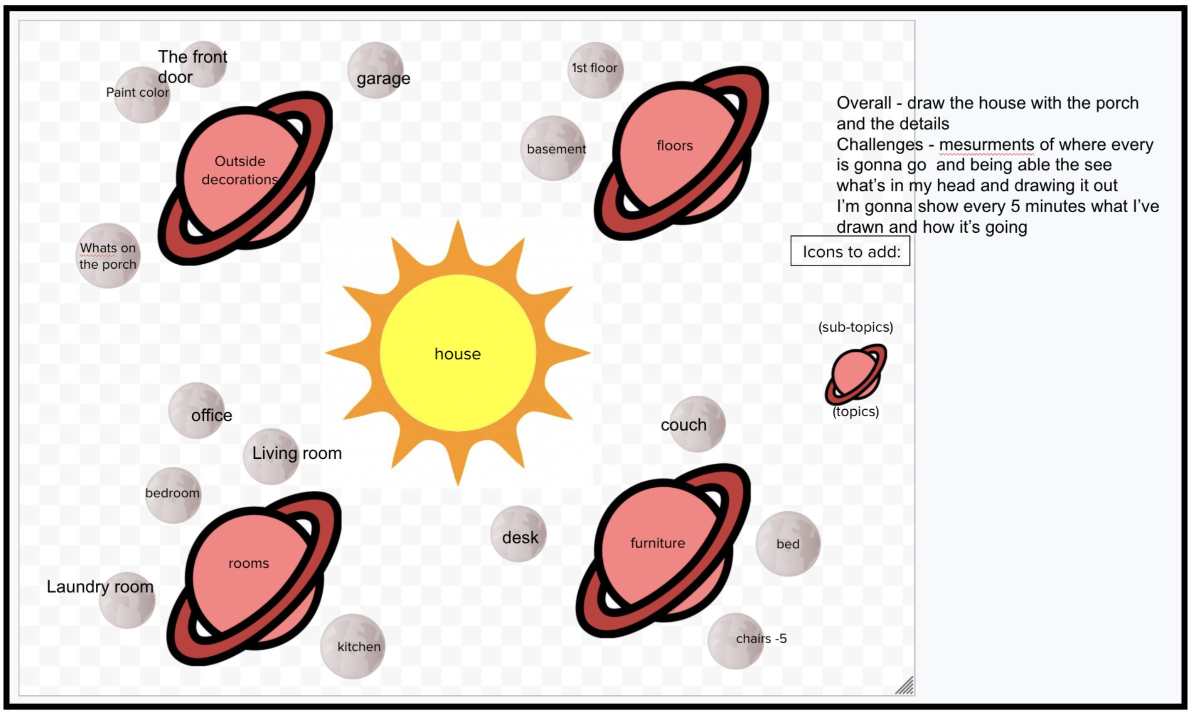
Figure 3 *Valerie's concept map, classified as challenge-oriented behavior*



When I asked further about her choice of topics for the planets, she spoke of previous experiences with her family and at school where she would run into issues that frustrate her, but learning to be patient with herself and her peers was key. Trying again with different solutions to an issue, not giving up too easily, and learning from her mistakes were lessons she learned from her family member. Her approach to thinking about documenting her progress on making was to preempt challenges she could run into, and in this case for the model house, she figured that her house may not be able to stand upright stably as she would use recycled materials such as cardboard and newspapers, thus she felt it was a vital point to include in her concept map. When prompted about how she might present how she builds her model house, she started writing steps involving her use of different materials at the side of the concept map to illustrate her process.

Top-Down Procedural Visualization Behavior. Sarah's concept map in Figure 4 depicts visualization of a top-down procedure to build a model house, where she breaks down the planets into "outside decorations," "floors," "rooms," and "furniture." Each moon that relates to the planet elaborates further about the content she wrote in the planet closest to the moons - for example, around the planet "rooms," Sarah wrote "laundry room," "kitchen," "living room" etc.

Figure 4 *Sarah's concept map, classified as top-down procedural visualization behavior*



Sarah's approach directly reflected her mental model about how a house looks like, and how she would build a model house that resembles a real house. When prompted further about how she would demonstrate details of the build process, she stated that she would use sketches to draw how certain sections such as the porch would look like, then measure the dimensions of rooms and floors to "see what is in (her) head." When further questioned about the cadence and frequency of drawing so that an external audience or her teacher might understand her progress, she added that she would “show every 5 minutes what (she has) drawn.” From Sarah’s example, we observe that her perspective towards process documentation involves illustrating her visualizations as much as possible of the final product that she is aiming for.

Overall, most students fell short of brainstorming multimodal strategies for documentation, such as combining photographs, audio recordings and text, unless I (the facilitator) gave them more options to think about multimodal strategies. The need for frequent prompting is also a key finding here, which indicates that the tool should be designed to facilitate a more structured process that students can follow. However, solely relying on the technological tool might not achieve the desired documentation outcome and goal. There still needs to be an environment and culture (most likely cultivated and guided by the teacher) that supports students’ documentation practices. Some students also had difficulty identifying main ideas or themes to write in the red planets to start with, and it was not apparent to them that the moons should relate to the planets until I explicitly told them. I wanted to construct a framework or an analogy that is immediately accessible to students, thus I concluded that the solar system analogy was not ideal because it involved a multi-layered dependence chain amongst its features.

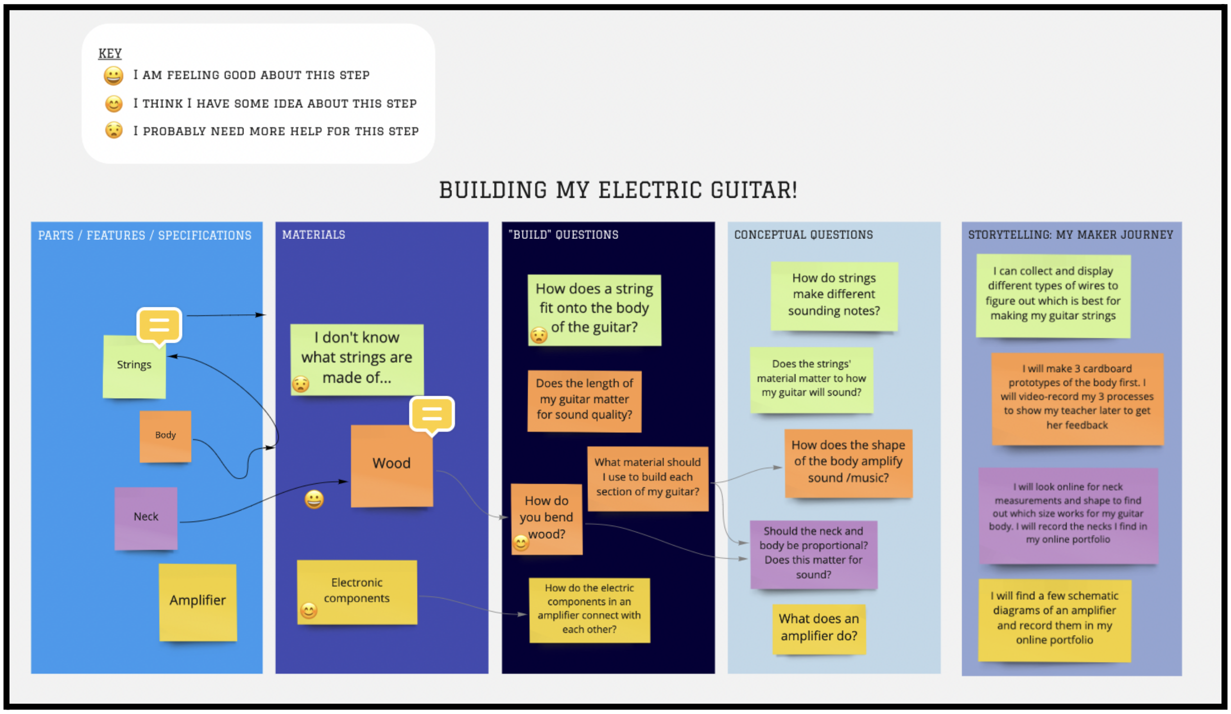
From Phase 1, I gathered that all three aspects - goals, challenges, visualizations - were essential in process documentation for formative assessment. This CoCreator App prototype in the form of a concept map template afforded students to focus on only one of these aspects, instead of all. Therefore, for the next iteration of the CoCreator App, I decided to build a tool that encompasses goals, challenges and visualizations with more concrete structure, to prompt the student more directly towards multimodal strategies of formative assessment.

Phase 2

Development of the Prototype

With regards to the iterative nature of design-based research methodology, my findings from Phase 1 will inform my design iteration in Phase 2. From my observations of areas where students struggled using the solar system analogy in Phase 1's prototype, I decided to reformat Phase 2's prototype using Collins & Ferguson's cross-product epistemic game (Ferguson, 1991), in order to help students visually connect their mental models from maker project theme to documentation method. In this design, I combined procedural approaches with conceptual questions and made room for students to explore different modalities of documentation, after observing from the first data collection phase that only a couple of students explored more than one pathway on a given concept map. Phase 2's prototype of the CoCreator App was built on Miro, a commercial collaborative software. For Phase 2, I prototyped a framework that allows the maker educator's collaborative role to be more explicit, and replaced the solar system analogy from Phase 1 with direct headers and prompts to stimulate discussion between the maker educator and student. A screenshot of a template prototype is shown below, with content from an example project "building my electric guitar":

Figure 5 *CoCreator App Prototype built on Miro (second design iteration)*



Category Scaffolds. These are represented by the five main rectangular blocks, titled "Parts," "Materials," "Build Questions," "Conceptual Questions," and "Storytelling: My Maker Journey." Although these blocks are placed side by side and may be read from left to right at the first glance, students do not necessarily need to use them from left to right. Rather, students could use the blocks in no particular order. These blocks are designed to prompt students towards thinking about how they would tell the story of their maker journey, thus leading them closer to identifying ways of documentation that would illustrate the successes and challenges of their maker journey for their own reflection and to share with peers and their teachers / mentors. "Parts" indicates parts of the product or project that the student will work on, "Materials" indicates materials that the student will use to build the project, "Build Questions" refers to questions that the student may have related to the construction process such as how to use a laser cutter for a certain step in the project, “Conceptual Questions” refers to academic or abstract questions the student may have related to scientific, artistic, or engineering-related concepts such as circuitry, and “Storytelling: My Maker Journey” is space for students to brainstorm methods of documentation to illustrate their construction processes, how they learnt new skills, and how they understood academic concepts related to their project.

Virtual Post-it Notes. Students can add as many virtual post-it notes as they would like onto the rectangular blocks to respond to the headers of the blocks. For example, under “Parts” for the electric guitar project, the student could write “Strings,” “Amplifier,” or “Neck” to brainstorm the main parts of the guitar that they need to build. Next, under “Materials,” students are prompted to figure out what types of materials their parts would need, how they might source these materials, and what kinds of materials would be feasible to use given logistical or environmental constraints. In Figure 5, students could write a material such as “Wood” if they know what material they would like to use, or they could write “I don’t know what strings are made of…” to indicate lack of knowledge about a topic, and potentially a to-do item to figure out what material their part should be made of.

Connectors. Students can use the connector arrows to link post-it notes from different blocks to show a relationship between the content written on the connected post-it notes. The example in Figure 5 shows a connection between “Neck” and “Wood,” demonstrating that the student understands that the neck of the guitar should be made of wood. This could prompt discussion between the student and teacher about whether the student will indeed choose to use wood when building the guitar, and types of wood the student might consider as different woods have different properties.

Emotion Key. This emotion key has three emojis listed on it for students to indicate their emotions at certain steps in their projects. The three emotions in the key are: "I am feeling good about this step," "I think I have some idea about this step," and "I probably need more help on this step." Students could place emojis next to their virtual post-it notes on the framework. These emojis are intended to stimulate discussion between students and teachers about students' confidence at various points in their making process.

Comments. Students and teachers can add comments (shown as yellow chat icons) to any of the virtual post-it notes to write additional feedback or questions pertaining to the content in the virtual post-it note. Similar to the emotion key, this comments feature is intended to stimulate discussion between the student and teacher during a synchronous check-in.

Implementing Phase 2

I implemented this version of the prototype at two physical sites in Singapore - a formal maker program at an elementary school and an informal afterschool makerspace for elementary and middle school students. I felt it was necessary to include both formal and informal learning environments for this implementation, because there are stark differences that constrain activities, learning and student-teacher interactions in these contexts. It was important that I note down findings from implementations at both formal and informal learning contexts to compare and contrast how students and teachers interacted with one another and with the CoCreator App. This implementation was conducted at the end of Singapore's academic year, where students were in a "post-examination" period, leading up into the end-of-year holidays.

At the elementary school, the maker program was scheduled as part of the students' mathematics class, as the maker educator's core teaching subject was mathematics. The maker program lasted for two weeks, where the students met six times throughout the two weeks to work on their projects. The maker challenge was to build the strongest bridge out of recycled materials. There were six teams of students, where each team had two students. Altogether, 12 rising fourth-grade students participated in this implementation at the school.

At the informal makerspace, students were part of a holiday program where they would work on individual or group projects. I observed five students doing individual projects, and a team of three students in a group project. These eight students ranged between fourth to eighth grade. This holiday program lasted for eight weeks (two months), and students would drop in depending on their availability - some came to the makerspace twice a week to nearly every day. The makerspace facilitators assigned each student to a maker mentor. In this study, I observed two maker mentors working with these eight students. This holiday program was very open-ended - the makerspace would support anything that students wanted to build, and also gave each student a budget to work with. Therefore, the students came up with a very wide range of projects: a medicine dispenser watch/wearable, a smart trolley for the elderly, a water filtration system, a burglar alarm, a mobile application for the national library, and a delivery drone.

To implement the CoCreator App, I first introduced the framework to the teachers and mentors to give them time to think about how they might introduce it to their students and use it to track their students' progress. The teacher at the elementary school decided that he would add reflection questions to guide students more explicitly in using the framework during class time, while the mentors at the makerspace holiday program used the CoCreator App to check in with their mentees during weekly meetings. I observed every session at the school's makerspace during their three-week program in-person, and observed weekly check-in meetings between the mentors and students at the informal makerspace, sometimes in-person and online, depending on the students' and mentors' choice on meeting venue. Nearing the end of the programs, I interviewed the maker educators at the school, and the students and mentors at the informal makerspace using interview protocols in Appendices C and D. I asked them questions about their documentation choices, how they figured out the types of artifacts they would document, and how they used the CoCreator App to meet their goals. I was unable to interview the students at the school makerspace due to scheduling constraints and year-end school closure, but was able to speak with them informally during observation sessions about their documentation choices and goals, following an outline similar to the interview protocol I had planned in Appendix C. During my observations, I looked out for instances when students discuss their projects with the teachers / mentors, references students / teachers / mentors made to content they had added in the CoCreator App, and examples when the content on the CoCreator App provided new insights to the teacher / mentors about students' work and thought processes.

Findings from Phase 2

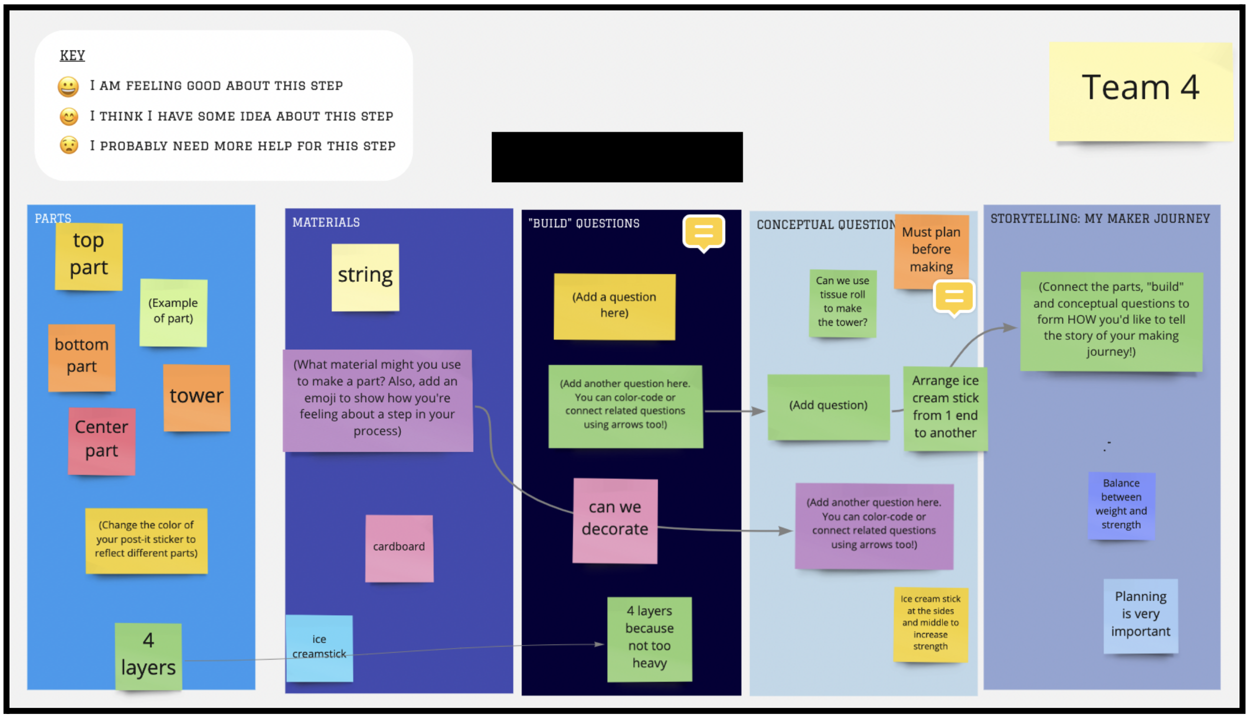
I observed that students in both formal and informal environments used the CoCreator App extensively during brainstorming before building, but used it less during prototyping. This was due to a combination of reasons - students generally found it a logistical chore to log onto a web platform during prototyping to engage in documentation or reflection, and they had time constraints during their in-person making sessions. Other students were not able to recognize the value of documentation for their maker projects, thus these students were not motivated to document, although their teachers / mentors reminded them to.

Documentation in the School Makerspace. For context: although this implementation occurred in a school makerspace during formal curriculum time, this maker program was part of a post-examination activity led by the maker educator (who was also the students' mathematics teacher). Hence, the maker program seemed closer to an informal afterschool activity, than a formal school activity with clear subject-oriented objectives.

Students in the formal makerspace were very dependent on their teacher regarding documentation and decision-making - I illustrate this with examples later in this section. The school maker educator carved out time for reflection at the end of each session, stated instructions for reflections explicitly, and played a large role in determining the students' mode of documentation (namely sketches, diagrams, photographs). While the CoCreator App proved to be a useful brainstorming tool, the current framework fell short of helping the students and teachers collaboratively identify documentation methods for the students' project. Students ended up relying heavily on their teacher's instructions on how and what to reflect on. Multiple students cited the reason that their mentor knew exactly what they were doing in real time, hence they felt there was little need for further documentation during prototyping.

Case Study: teacher-Guided Documentation. Figure 6 below shows Team 4's documentation on the CoCreator App, which the pair of students (Brendan and Iman) used mostly during the first two out of six sessions, since the first two sessions focused on brainstorming and planning.

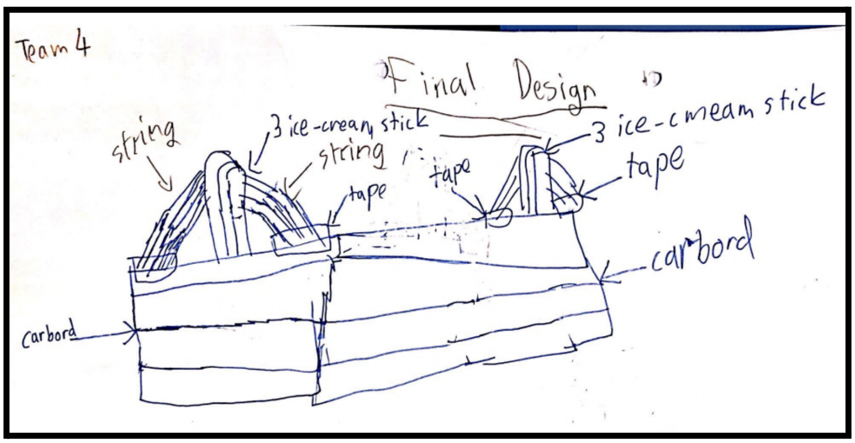
Figure 6 *Brendan and Iman's framework on the CoCreator App, focusing on virtual post-it notes under "Parts," "Materials," and "Build Questions," and connecting arrows between "4 layers" and "4 layers because not too heavy."*



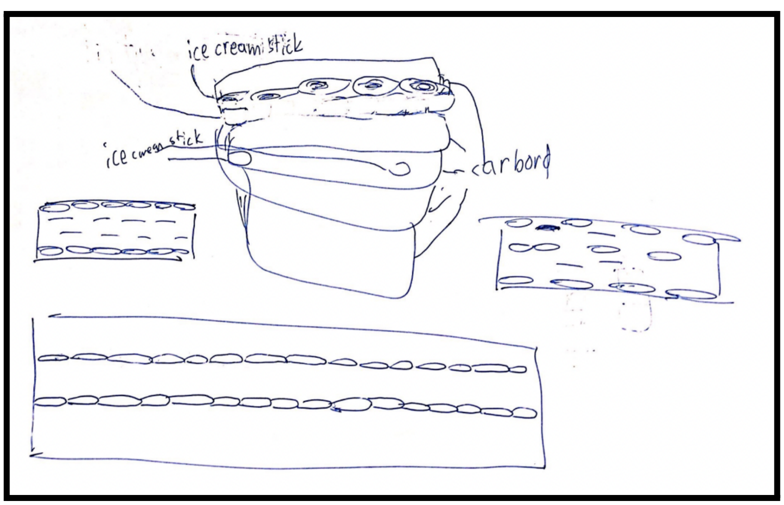
As their teacher had clearly defined that the task for the next two weeks was to build the strongest bridge that they can out of recycled materials, Brendan and Iman immediately thought of cardboard, string and ice-cream sticks - all of which they had used in previous maker projects, thus they were familiar with these materials, and were able to note down these materials on the CoCreator App quickly. Parts of the bridge were fairly straightforward to brainstorm too, as they decided that the bridge should have at least a top, center and bottom part. Regarding "4 layers" and "tower," Brendan and Iman latched onto an idea that their bridge should have a tower, likely inspired by aesthetic photographs that their teacher had shown to them at the start of the first session, but not really considering that a tower might add unnecessary weight to a portion of their bridge (which they realized later after testing their first bridge prototype). Their sketches on paper in Figure 7, which they organized in a folder that they submitted to their teacher, illustrated their visualizations of how their bridge would look, their edits to the bridge design after discussion with their teacher, and their reflections after the strength-testing sessions:

Figure 7 *Brendan and Iman sketch their first and second bridge's designs, before and after incorporating synchronous feedback from their teacher regarding ice-cream stick placement to strengthen their bridge design*

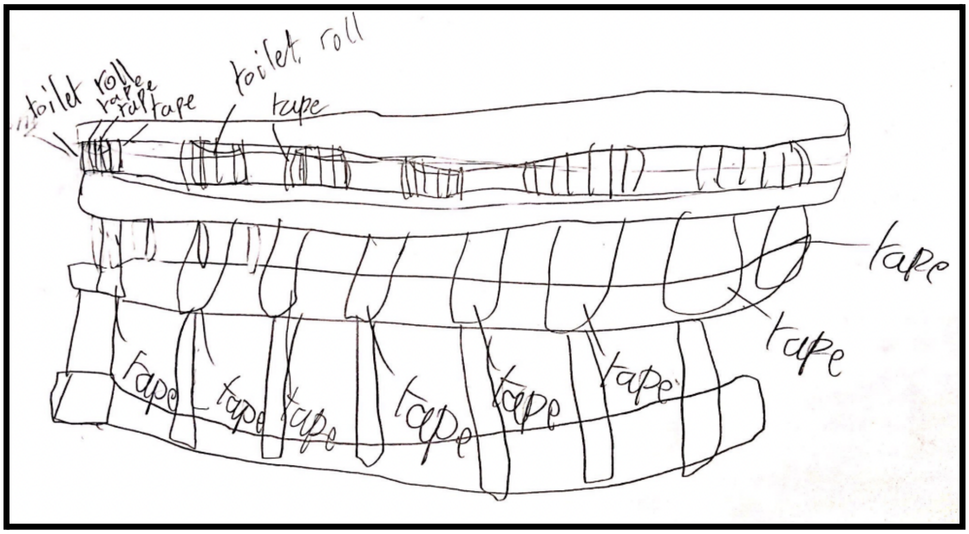
Before:



After:



The bridge Brendan and Iman ended up making:



Prior to this sketch in Figure 7, Brendan and Iman realized during their first test session that their bridge would sink in the middle quickly when weights were placed on it, thus they consulted their teacher about how they could make their bridge withstand more weights. Their teacher gave them a hint that this could be solved by changing the arrangement of their ice-cream sticks on the bridge. Originally, they stuck their ice-cream sticks lengthwise side by side in a straight row on cardboard, but the teacher prompted them with hypotheses about how the cardboard might bend less if ice-cream sticks were placed in different rows. This discussion motivated the students to try different arrangements of ice-cream sticks, and the sketches helped them compare the hypotheses. These students had not learnt about physics and stress yet in science classes, thus these were new concepts that they encountered while building the bridge.

When Brendan and Iman compared their second bridge design with their previous one, they wrote on a looseleaf sheet of paper:

> The new design have more strength from the old design because of the addeitio (addition) of the chop stick and ice cream stick.

In their final reflection, they responded to prompts the teacher had written on the whiteboard: 1) Original design; 2) What happened in testing 1; 3) Improved design; 4) Problem during making; 5) What happened in testing 2; 6) What I have learned:

> <u>Our Journey of making a bridge</u>
> We found that testing 1 our bridge can hold 18 boxes but when we upgrade our bridge it can hold 23 boxes. We added some ice creams and one layer of cardboard to make it stronger.

Here, their teacher guided the reflection process because he felt that students would not be able to respond meaningfully to the broad prompts on the CoCreator App. If students are not specific in their reflection responses, the teacher stated that this would not be useful for him either, because he would not be able to pinpoint areas that students have understood and areas where they need further clarification or assistance. (Appendix H includes more of Brendan and Iman's illustrations.) This insight signaled that there is a need for formative assessment, but the CoCreator App should have more structured and direct reflection prompts that students can understand to answer productively.

The CoCreator App may have helped students like Brendan and Iman figure out basic parts, materials and build questions, but the prompts were too broad for this group of students who had never documented maker projects in the past. The students were used to receiving their teacher's guidance and instructions synchronously in class, thus the CoCreator App was minimally helpful in stimulating discussion between the students and teacher about their progress. Although the students moved away from the CoCreator App during prototyping and testing, the sketches of their design made on paper (another form of documentation) helped them visualize new, potentially abstract concepts about material science that they had not learned in formal curricula. For this case, Brendan and Iman were able to see some value in sketching or noting down new concepts that would help them improve on their project, but these sketches were not prompted and could not be collected by the CoCreator App. As I'll show in chapter 5, this prompted one of the key features of the next iteration of the CoCreator App, the use of students' photographs of work done in class as the main modality. If students drew sketches, they would take photographs of their sketches to upload onto the CoCreator App and attach hashtags onto these photographs for organization, so that their artifacts will all be stored on the CoCreator App, visible to teachers for feedback too.

Documentation in the Informal Makerspace. Students in the informal after-school makerspace worked on a two-month project, while students in the school makerspace worked on a two-week project, where they had sessions in the makerspace three times a week. As students in the informal makerspace had a longer time period to work on their projects with closer 1-1 supervision from their mentors, these students were more proactive in figuring out a variety of methods of documentation that suited their workflows. The makerspace director also reminded students and mentors to track their challenges, successes, and pivots in decision-making, and organized a designated workshop for the students to explore storytelling and documentation, thus these reminders likely constituted towards students' proactivity in documentation overall.

The most common documentation behavior amongst students on the CoCreator App was adding diagrams, sketches, content about how they would build their prototypes, and sometimes additional research from online sources about questions they came across. In addition to these forms of visual and textual documentation on the CoCreator App, a student compiled a notebook of experimental results, while another student messaged ideas to himself via WhatsApp every time he worked on his project. Each student in the informal makerspace had a different method of documentation that they identified for themselves. Students and mentors used the CoCreator App extensively for collaborative brainstorming by sharing images, sketches and website links on the platform, but during prototyping they relied more on synchronous feedback and referred intermittently to notes or sketches previously added onto the CoCreator App. During prototyping, students developed their own methods of taking notes about their progress, and oftentimes these notes or photographs were compiled elsewhere (such as on their smartphone's Photos application, or on paper), not on the CoCreator App. Because these notes were not on the CoCreator App and students minimally communicated about these notes, the mentors did not know that students were keeping track of their own work in these manners until nearing the end of the project, when it was time to discuss how the students would present their projects on the showcase day. For students in groups, there was also minimal communication amongst peers about how they kept track of their own progress, which sometimes led to misunderstanding about completion of certain tasks when different groupmates stepped in.

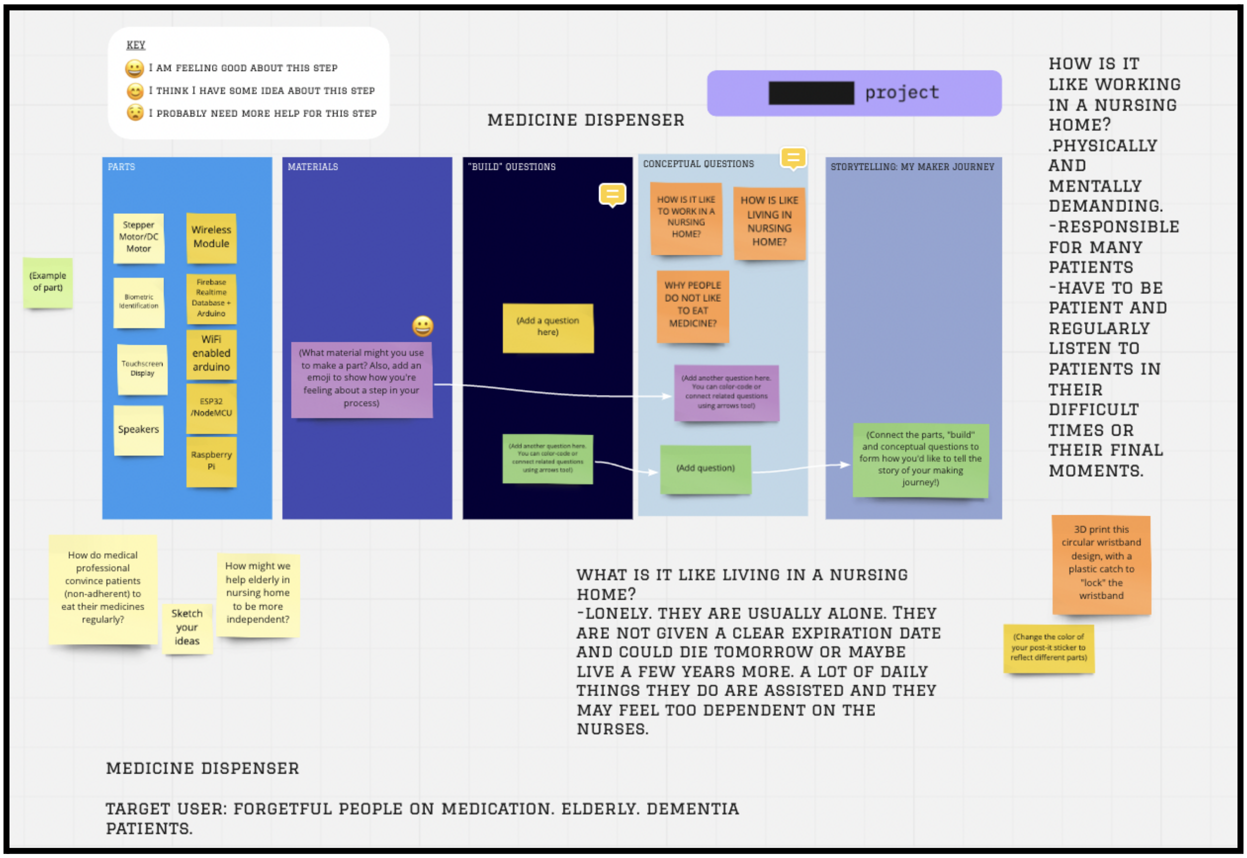
The table below demonstrates the variety of maker projects students engaged in, and their choices of documentation methods during prototyping:

Table 4 *Students' Projects and Choices of Documentation Modalities at the Informal Makerspace*

Student	Project	Project Description	Documentation Modality / Modalities
Dan	Medimind	Dan built a watch that has a pill dispensing feature, so that users would be reminded to take their medicine regularly and on time.	CoCreator App; personal to-do list on WhatsApp; code snippets on Slack
Damian	H_2oly Water	Damian did extensive online research on water purification systems because he was interested in addressing social and health issues related to water contamination. He built a filtration system that detects lime buildup that affects water flow and leads to rust formation.	CoCreator App; booklet of experiment results
Dylan	Collapsible Smart Trolley	This is a power-assisted trolley that helps the elderly transport heavy items. Dylan designed this trolley to be collapsible so that it can be stored efficiently at home.	CoCreator App; sketchbook
Yusuf	PlantLarm	Yusuf built a home alarm system, hidden beneath plants, that detects human movement (potentially burglars) using infrared sensors.	CoCreator App; personal to-do list on Notes mobile app
Russell, Jasim & Harjit	The Drone Project	This team of 3 students learnt to build a drone from scratch, with the idea of delivering food and medical supplies during humanitarian missions.	CoCreator App (all); notes and sketches on looseleaf paper (Jasim); Russell and Harjit hardly documented

Case Study: Documentation for Personal Recall and Mentor Communication. Figure 8 below shows how a student Dan used the CoCreator App for his project - building a medical dispenser - and later, how he figured out his own form of documentation during prototyping. Dan was an eighth-grade student with some previous experience in making at school and at this afterschool makerspace. Images in Figure 8 show most of his brainstorming and planning stages.

Figure 8 *Dan's artifacts about his project Medimind on the CoCreator App*



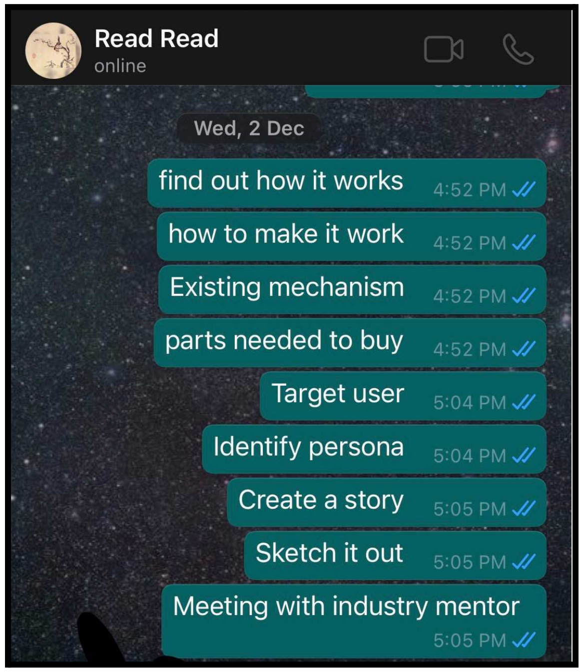
During Dan's initial discussions with his mentor, his mentor emphasized that he should find out more about how people use medical dispensers to figure out pain points, and to narrow his focus to a target user. Dan first started using the CoCreator App's "Conceptual Questions" column, because from conversations with his mentor, he decided that questions around user needs should be clarified before moving on to ideating and prototyping. Under "Conceptual Questions," Dan wrote questions such as "How is it like to work in a nursing home?" and "Why people do not like to eat medicine?”. After speaking to caretakers of elderly patients, Dan wrote answers to these questions below the column. With assistance from his mentor, Dan also added other questions on user needs such as “How do medical professionals convince patients (non-adherent) to eat their medicines regularly?” and “How might we help elderly in nursing homes to be more independent?” When asked why he didn’t add these additional questions under “Conceptual Questions”, Dan mentioned that he felt these were questions that would prompt him towards design ideas, and not necessarily fundamental questions on the user experience.

Around his questions and answers on the CoCreator App, Dan added notes on building and use of materials, such as “Could a timer be built into the Arduino or Microbit?” and “Do a quick prototype using cardboard / wire / prototyping materials first”. Over the next couple of weeks of individual brainstorming and weekly check-in sessions with his mentor, these questions led Dan to ponder more about electronic components that could be added into the build of the medical dispenser. He did online research to identify key features of existing dispensers, and smart features that he thought would optimize caretakers’ or patients’ challenges around taking medicine regularly. Dan noted functions and features of dispensers, such as an “intercom system,” “SOS button,” and “health systems to alert guardian irregular activity.” Although these were Dan’s preliminary brainstorm bullet points, these points drove a major portion of his conversations with his mentor in figuring out the feasibility of features he proposed.

As he started prototyping, Dan proactively wrote a word document (Appendix I) about *Medimind*, the title he used to name his project. During the interview, he stated that he chose to write a word document to portray his mid- to later-stage ideas in paragraphs, rather than use virtual post-it notes on the CoCreator App framework because he felt he could develop his ideas more deeply through text. Nevertheless, he uploaded the word document next to the CoCreator App framework, because he knew his mentor would check his updates on the CoCreator App asynchronously. Dan also included his latest sketch of *Medimind*, which he envisioned as a wristwatch (wearable) instead of a traditional medicine box dispenser.

When he started building his prototypes in the makerspace, Dan populated this CoCreator App less often, using it mostly for reference to previous designs. During his interview, he stated that he found several ways of keeping track of his own prototyping stages that worked better than logging into the CoCreator App, mostly for himself and sometimes with his mentor in mind. During prototyping, he felt that logging onto the CoCreator App (a web platform in Phase 2) while in the middle of making was disruptive, thus he wanted to use more seamless ways of recording information. As he is very familiar with the WhatsApp mobile application, he would text himself to-do items and reminders about the project as and when he gets inspired or thinks of steps that he is about to execute. For example, the screenshot below in Figure 9 shows his personal notes and reminders about *Medimind*. He would pin this chat titled “Read Read” at the top of his WhatsApp interface, so that it would be easy for him to access at any time of the day. Dan did not share these WhatsApp notes with his mentor at all - these were entirely for his own personal use to keep track of his ideas and reminders.

Figure 9 *Dan's documentation to himself on WhatsApp, integrating tasks from his maker project into his personal to-do list*



When it came to coding the mechanical behaviors of the *Medimind* tool, Dan stated in his interview that he would share code chunks with his mentor via the makerspace program's Slack workspace, because it was his and his mentor's most used asynchronous communication platform. As he was new to Arduino[4], he knew that he would run into bugs, and that sometimes he might not be able to open Arduino files on his home laptop due to its software settings. As a result, he felt it was important for him to share the code entirely with his mentor for guidance in debugging. Although he sent code chunks to his mentor via Slack typically at the end of an in-person prototyping (Appendix I), he occasionally sent to himself (via Whatsapp) shorter code snippets of where he thought a bug was, with a note to try debugging in a certain manner later, particularly if he ran out of time debugging during the in-person prototyping session where he usually would receive immediate synchronous assistance from his mentor.

[4] An Arduino is a microcontroller used to build interactive electronic objects and digital devices.

Overall, Dan recollected that he found documentation helpful primarily because he knew he wanted to present different stages of his construction process at the project showcase to take place at the end of the maker program, thus he saw the need to organize his ideas, sketches, code, and low and high fidelity prototypes. Although the maker program had provided a Google Slides template for him to follow for his showcase, he did not use it at all, because he found that organizing his stages of construction based on how he envisioned his chronological process made more sense to him. Instead, he referred to brainstorming notes and sketches on the CoCreator App, asynchronous conversations and notes that were on his Slack chat with his mentor, and photographs and videos of his prototyping process that he saved on his smartphone.

Apart from documenting for the showcase, Dan cited that documenting during the brainstorming phase on the CoCreator App was particularly helpful as his mentor would review any new updates (comments / virtual post-it notes / word document) he made to the framework before their check-in session, and his mentor would ask follow-up questions that he had not considered. For example, his mentor asked many more questions regarding components, equipment for building, practicality from the users' perspective, and even provided him with books and online resources to narrow the target audience he would build for.

Later, although he shifted to using WhatsApp and Slack for documenting his prototyping stages, he found that his notes, photographs, and videos helped him recall steps that he had worked on, and where to pick up from where he left off at a previous prototyping session. With regards to the CoCreator App's user interface, Dan felt that there were limitations in showing his progress with prototyping, because he did not want the space to be cluttered with too many photographs or videos, let alone code chunks. To him, the CoCreator App also lacked a chronological outline, which he figured would be helpful in tracing his progress over the weeks.

Key findings from Phases 1 and 2 about the design of documentation tools to assist elementary school students include the following:

- Students should be given choices and autonomy regarding the modality/modalities of documentation they would like to use;
- Time and logistics constraints in a formal learning environment may restrict students' exploration with modalities of documentation;
- Students do mention and discuss social-emotional challenges related to their maker projects, so the documentation tool should accommodate
- Regular and visible engagement with students' artifacts from teachers and mentors is essential in cultivating a culture for documentation.

These points will drive Phase 3's design iteration and analysis with the findings I collect from Phase 3. I also return to these points in Chapter 6: Discussion.

Chapter 5: Second Implementation of the CoCreator App

This dissertation explores the implementation of the CoCreator App, a technology-enhanced tool for formative assessment (documentation and feedback). This chapter presents findings from Phase 3 of data collection, which is the second implementation of the CoCreator App. Data was derived from field notes of classroom observations, interviews, and students' artifacts.

As this study follows a design-based research (DBR) methodology, findings and data analysis from Phases 1 and 2 contributed to the development of the high fidelity prototype implemented in Phase 3. Later in this chapter, I describe how the Phase 3 prototype was designed and developed, then present case studies on students' documentation processes and interactions with the prototype, their peers, and their teachers.

Key Changes from the First to Second Implementation

There were various design challenges to take into account from the first to second implementation. Below, I describe the challenges faced, and the implementations that I tried in Phases 1, 2, and 3. Table 5 later summarizes the main changes in design features across all phases.

Design Challenge #1: Providing students with their choice(s) of modality of documentation

In Phase 1 (with the solar system concept map analogy), students typically thought of one modality of documentation that they were already familiar with and adhered to it, and minimally brainstormed or explored other possible modalities. In Phase 2, the CoCreator App design was built on a web platform using Miro, so it afforded more opportunities for students to include artifacts of different modalities. Prompts were provided in the CoCreator App to guide students to think about a variety of modalities for documentation, and teachers / mentors were reminded to facilitate this discussion about documentation with students too. From Phase 2, because some students were overwhelmed with too many different modalities of documentation, yet some students were still less adventurous in exploring different modalities, Phase 3's CoCreator App mobile prototype implemented a structure that used primarily photographs, hashtags, and text (for reflection) to guide all students through documentation and reflection.

Design Challenge #2: Understanding the Structure / Analogy of the Tool

Phase 1's The solar system analogy was used to guide students to plan their maker projects and think about documentation methods they would use, but students either were confused with the solar system analogy or did not use it as planned. I removed the solar system analogy from Phase 1 for Phase 2's design. Phase 2 used a framework with sub-headers: *Parts, Materials, Build Questions, Conceptual Questions, Storytelling: My Maker Journey*. These sub-headers were directly worded so that students can understand them easily. Students were able to be more productive with the first four sub-headers, but not so much for *Storytelling: My Maker Journey*, because this was a fairly new term and practice to many of them. Therefore, I decided to incorporate elements of these sub-headers into prompts in Phase 3, and hard-coded a more linear structure on the mobile application whereby students had to select hashtags for each uploaded photograph and self-report a confidence level before they could successfully upload a post on the CoCreator App.

Design Challenge #3: Representing and communicating social-emotional feelings associated with making

Phase 1's preliminary prototype did not have specific designs for students to note down social-emotional feelings. Two students from Phase 1 spoke extensively about potential social-emotional challenges that they felt they would experience during making, hence this prompted me to ponder more about including social-emotional feelings as part of documentation. Phase 2's prototype included an emoji key to denote three different types of feelings towards certain steps of the project. However, students rarely used the emoji key. If they did, they would tinker with and use many other emojis, apart from the emojis stated in the key. To provide students with a wider spectrum to describe and interpret their emotional states, I decided not to include an emoji key in Phase 3's prototype. Instead, I built a confidence level chart, where students self-report their confidence levels based on certain tasks they are doing for their maker project, then visualize their confidence levels over the course of the day and weeks. It is important that students are self-aware of their social-emotional states when engaging in activities that may cause both positive and negative feelings (examples of positive feelings include high confidence, elation, excitement; examples of negative feelings include lack of confidence, frustration, uncertainty etc.). I wanted to use this confidence level chart to capture data about how students perceived and reflected on their own and their group's emotions revolving around confidence towards a task.

Design Challenge #4: Providing and receiving feedback

Phase 1's prototype did not have specific designs for teachers to provide synchronous or asynchronous feedback to students. (Teachers were not involved as participants in Phase 1.)

Phase 2's prototype was used by teachers / mentors and students, whereby the teacher / mentor would check students' documentation asynchronously, then provide written comments through the Comments feature, or in-person synchronously when they meet the students. I noticed that some students in Phase 2 had difficulty responding to the broadly worded prompts embedded in the CoCreator App, and some students missed the prompts entirely. Students and teachers also hardly used the Comments feature because it was attached as a small speech bubble at the corner of the interface, which was easy to miss. I decided to add clear defined textboxes in Phase 3's prototype for students and teachers to communicate asynchronously in the app regarding feedback, in addition to feedback provided synchronously in class. These textboxes also included more specifically worded prompts for reflection that elementary school students should understand without seeking adult clarification.

Table 5 *Changes made in design features from the first to second implementation*

Design Feature	Phase 1	Phase 2	Phase 3
Process Scaffolds	Solar system analogy's components: Sun, planet, moon	Columns with headers: Parts, Materials, Build Questions, Conceptual Questions, Storytelling: My Maker Journey	Steps built into the app to create a post on the mobile app: take photographs, select hashtags, enter confidence level.
Reflection Prompts	None	Prompts are provided in some sample post-it note entries	Prompts are provided in the reflection textboxes
Representation of Emotions during making	None	Emoji Key with 3 emojis to represent: 1) I feel good, 2) I have some idea, 3) I need help	Chart Visualization, using self-reported confidence level scores

Feedback	None	Comments feature (could be used by the student or teacher)	Textboxes for feedback from the teacher to student and vice versa

Phase 3

Development of the Prototype

The second implementation of the CoCreator App involved building a mobile application of the CoCreator App with largely different features from the web platform version in Phase 2. Designed to be used on a mobile device, this version of the CoCreator App has a dual interface for the student and teacher.

Student Interface. The CoCreator App's design for the student interface includes a post for students to create visual updates, log their daily levels of confidence, and add hashtags that categorizes and describes their updates. The CoCreator App then compiles this data into a weekly chart visualization, where students can view their progress and levels of confidence over the course of one or multiple class sessions in a week. On the weekly chart visualization page, students would be prompted to write a textual reflection of their wins and challenges, and attach this reflection to the chart for their own documentation. Teachers may browse through students' reflections asynchronously. Students are also able to filter their posts via hashtags to view their progress over the course of multiple weeks for a particular skill, content area, or theme. Students are able to review their posts at a later date, by either clicking on the week where they posted, or by clicking a hashtag to view past photographs from previous weeks that are related to the chosen hashtag.

Design Feature: Hashtag. In Constructionist design, it is important that students have the choice to pursue projects or topics that have personal meaning and professional value. And yet, when all students in a class are designing different projects, it can be challenging for the teacher to examine themes and ideas across student work. To this end, the CoCreator App invites students and teachers to collaboratively generate a shared dictionary of hashtags that will be used to associate each student's post with a particular concept, topic, or skill. Because students are involved in choosing the hashtags, students may reveal their own understanding of a specific concept, skill or process through how they generate a hashtag. A hashtag will enable teachers to easily view all photographs associated with that particular hashtag. For example, upon clicking the hashtag *#makeymakey*, teachers will be able to view all photographs that the students tagged as #makeymakey. Likely, these photographs will feature the MakeyMakey microcontroller in it, perhaps in the middle of tasks that students are working on with the microcontroller, since these photographs are also connected to the students' posts that include their self-reported confidence level scores and any text reflections. The hashtags would be a form of data collected for analysis.

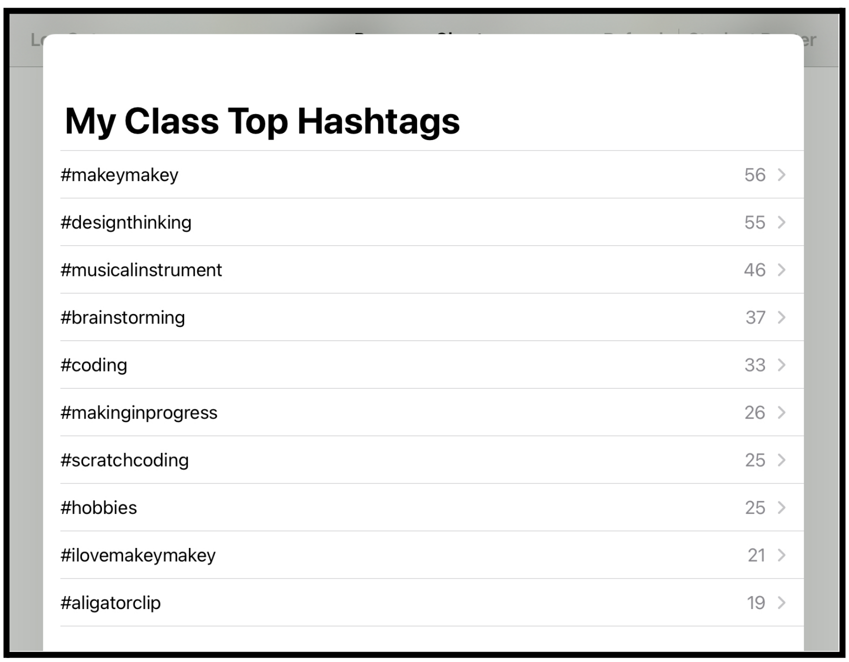
During data collection, students collaboratively create a "hashtag dictionary" with each other and their teachers, so that they come to a consensus about which phrases they think are meaningful and thus important to use to describe their maker projects. This points towards the constructionist theoretical notion that students should produce personally meaningful artifacts to learn, thus this tool (the CoCreator App) and its feature (hashtags) should add value to how students conceptualize and understand the processes and skills they are learning. This step is to limit the variety of similar hashtags that point to the same skill or concept (for example, from this group of hashtags "#circuit, #circuitry, #circuits", students should choose only one hashtag to include in their dictionary).

In addition to creating a "hashtag dictionary" with other classmates and choosing their own hashtags for individual updates, students are also able to select a specific hashtag to review all updates associated with that hashtag. This provides a chronological view of all of the student's updates related to a particular skill or concept, and prompts the student for a textual reflection regarding how they have developed this skill or concept over the past time period.

Design Feature: Chart Visualization. Basing off the cognitivist theory, this chart visualization feature's objective is to assist students in building rational mental models of concepts that surface in their maker projects. The CoCreator App generates a weekly chart to illustrate the student's self-reported scores of confidence levels, with a textbox space for the student to write their reflection on the past two weeks of progress. This can be viewed as a weekly progress update, and as a potential talking point if the student checks in individually with the teacher. The teacher is also able to view the student's chart and reflection, and provide comments asynchronously. For example, if a student finds himself struggling with the topic of closed and open circuits when working on the MakeyMakey, he may self-report a lower score on the chart to indicate his struggle. When he reviews this chart later on his own or with his peers or teachers, this could be a discussion point to review the concept of closed and open circuits to make sure that he has understood the concept, thus enabling the process of reflection through the student's maker journey.

Teacher Interface. The CoCreator App allows teachers to track individual students and view overall class progress. Important features include the comment function where teachers can comment on students' reflections on their chart visualizations or reflections on a particular hashtag, and the ability to view the class' top hashtags and take personal notes on where students are at with a specific concept or skill. Figure 10 below shows a ranked list of hashtags that students in the class used. When the teacher clicks on a hashtag such as #makeymakey, the teacher will be able to view all 56 posts that students have generated and tagged as #makeymakey. Most likely, these posts will have content and photographs related to students' projects when they were using their MakeyMakey kits.

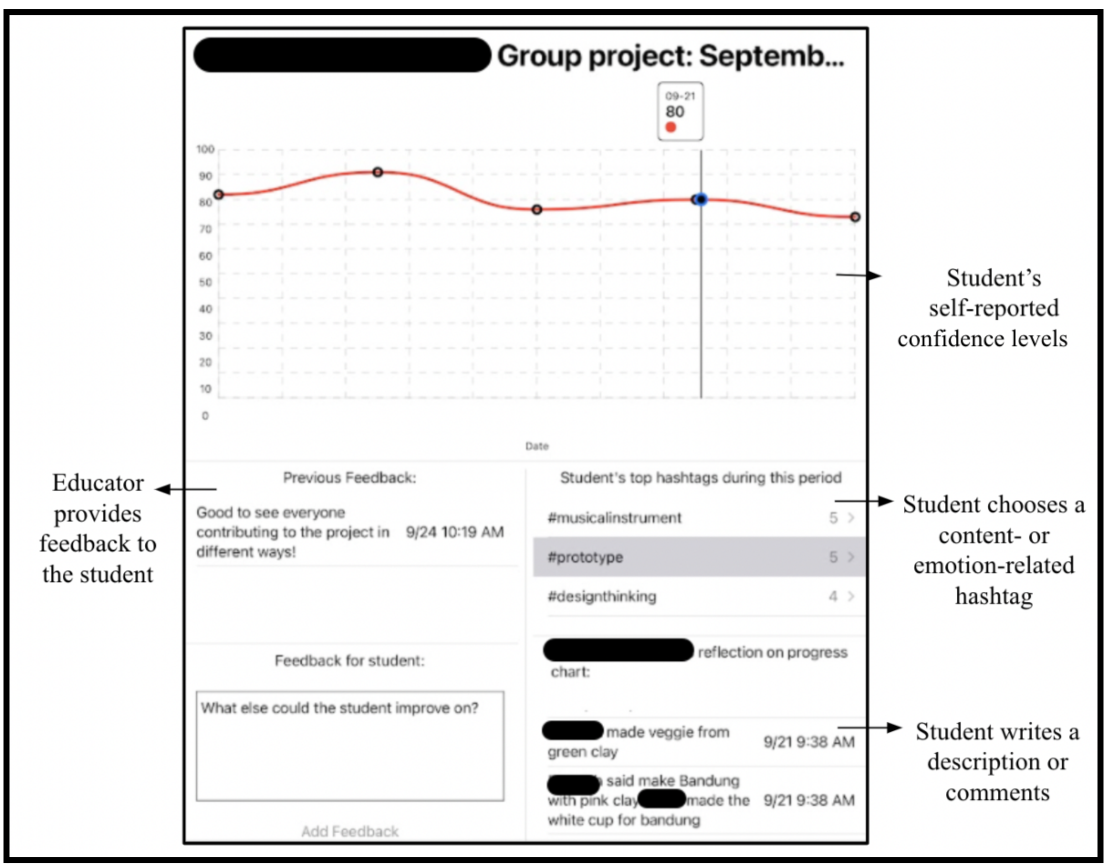
Figure 10 *The class' most frequently used hashtags on the CoCreator App*



In the spirit of continuous formative assessment, teachers would provide students with feedback synchronously or asynchronously via the platform. From the reflections and types of artifact updates that students post, teachers can gauge the various ideas and challenges students encounter in their maker projects, and the range of projects in the class. From how students tag their updates using hashtags and from the hashtag review of specific hashtags, teachers can also ascertain how students are categorizing and organizing their work, providing a window into students' scope of ideas and challenges that they encounter.

In sum, the CoCreator App was developed to encourage students to upload photographs of their works-in-progress with hashtags related to content and emotions, to self-report confidence levels throughout their maker classes, and to input comments or descriptions about their work in a text box below. Teachers are notified about new posts that students make on their account, and also have text boxes where they are encouraged to provide feedback to students. Students receive a notification when the teacher comments on their posts. Figure 11 below illustrates an overview of features on the CoCreator App's interface.

Figure 11 *The CoCreator App's interface and features*



Implementing Phase 3

Phase 3 involved a total of six 1.5-hour observations of a maker education program with 23 assenting students during formal curriculum time at an all-boys' elementary school in Singapore. Nearing the end of the maker program, I conducted hour-long online interviews with the two maker educators and half-hour online interviews with nine students. These nine students were selected based on their range of engagement with documentation and feedback. 5 of these 9 students were documentation leaders for their teams, while the remaining 4 were active groupmates who minimally engaged in documentation. Before the start of the maker program, I had preliminary meetings with the two teachers to brainstorm how we would introduce the CoCreator App to students at the first lesson. I also provided the teachers some time to familiarize themselves with the prototype.

This long-term maker program occurred during two combined Visual Art and Music periods, led by the Art and Music teachers (who were also the school's lead maker educators). The teachers introduced the students to the design thinking framework, and gave an overview of the project theme that will be covered during the term. For the first couple of lessons, students learned the fundamentals of coding on Scratch and circuitry using the MakeyMakey kit, then formed groups to work on their longer term projects. These were the main guidelines that students received from the teachers regarding the group project: Students were to create a musical instrument out of recycled and art materials, based on the hobbies and preferences of non-teaching staff members that the students interviewed. This musical instrument should play at least one Singaporean folk song that they would have learned to code, which should be programmed using Scratch and MakeyMakey. Similar to the previous chapter, all student names presented in this chapter are pseudonyms.

In class, the teachers instructed students to use the CoCreator App throughout the 1.5-hour period to document activities and assignments they are working on. The teachers encouraged students to document photographs of works-in-progress, instead of only showing finished work. To provide more structure to documentation, the teachers assigned at least one student per group to be the "documentation leader" so that this student will be responsible for taking photographs of his group's work and reminding his group mates to document any individual work. The teachers also suggested that students should take at least five photographs spaced out throughout the 1.5-hour period, and not a bunch of photographs during the last few minutes. Students were assigned in groups shown in the table below:

Table 6 *Student Groups in Phase 3*

<table>
<tr><th>Group</th><th>Students</th><th>Documentation Modalities</th></tr>
<tr><td>A</td><td>• Zihao (documentation leader)
• Pratama
• Edwin
• Ben
• (5th student did not consent to participating in the study)</td><td rowspan="3">CoCreator App; Sketchbook / Notebook (paper)</td></tr>
<tr><td>B</td><td>• Deepak (co-documentation leader)
• Dara (co-documentation leader)
• Ivan
• Sahil
• (5th student did not consent to participating in the study)</td></tr>
<tr><td>C</td><td>• Kian Tat (documentation leader)
• Kevin
• Ian
• Donald</td></tr>
</table>

	• Yilan	
D	• James (documentation leader) • Damian • Gung Heng • Aman • Saadiq	
E	• Junfeng (documentation leader) • Zhi Lim • Declan • Colin	

For my findings, I elaborate on 1) observations I made regarding students' documentation practices and perceptions of formative assessment that I gathered through students' interviews, and 2) feedback and communication between students and the teachers that lead to students' reflection about new knowledge of concepts or skills. I will return to my research questions using insights from these findings in the discussion in Chapter 6 later.

Findings from Phase 3

I elaborate on my findings from Phase 3 in two sections: 1) documentation practices, and 2) feedback. Under documentation practices, I provide insights on three students who are documentation leaders of three different groups. Then, under feedback, I present instances of synchronous (in-person) and asynchronous (in-app / offline) feedback between the teachers and students. Later in Chapter 6: Discussion, I return to these anecdotes to address my research questions on documentation providing insights to students and teachers, and documentation facilitated by a collaborative tool for reflection of new knowledge.

Documentation Practices. From Phase 3, I categorized my main observations on each group's documentation leaders' practices during their projects into the following personas: the "leader", the "follower", and the "diplomat". I categorize them in this manner to illustrate how their different styles of documentation affect group dynamics, and as a result affect how students form insights or reflections about their making processes during their projects. This table below demonstrates the categories of documentation styles:

Table 7 *Documentation Styles amongst students: "Leader," "Follower," "Diplomat"*

Criteria	"Leader"	"Follower"	"Diplomat"
Style of documentation (spectrum of individualistic to democratic)	● Takes charge of the making and documentation process ● Understands the task assignment well, and steps that need to be completed during class time	● Does not take charge of the making and documentation process	● Takes into account his groupmates' opinions and thoughts around the making and documentation process before documenting
Reliance on peers	● Hardly relies on his groupmates' directions for documentation ● Sometimes directs his groupmates on what to do and how to prepare the artifacts for documentation	● Often relies heavily on his groupmates' directions on what and how to document	● Sometimes relies on groupmates' directions on what and how to document ● May chip in ideas or counter suggestions if he does not agree with his groupmates
Reliance on teachers	● Needs occasional reminders from the teachers to document, ● Generally documents on his own and proactively	● Needs occasional reminders from the teachers to document ● Able to document on his own, with groupmates' input	● Needs occasional reminders from the teachers to document ● Able to document on his own

Value of Documentation	● Provides a response as to why documentation might be useful ● Clearly states at least one goal / need for documentation	● Provides an unclear response as to why documentation might be useful	● Provides an unclear response as to why documentation might be useful

Sometimes, students might oscillate between these categories. The anecdotes below illustrate students' approaches to documentation based on these categories.

The "Leader." Zihao was his group's documentation leader and exhibited characteristics closest to the category "Leader." On the first criterion - style of documentation, Zihao took charge of his group's project early on during brainstorming and design thinking, observed through in-class sessions. He actively learned to use the CoCreator App for his individual assignments, and later for his group's project. This excerpt from Zihao's interview indicates that he and his groupmates believed that he knew how to navigate the CoCreator App best amongst his groupmates, so he became the person in charge of doing documentation for the team:

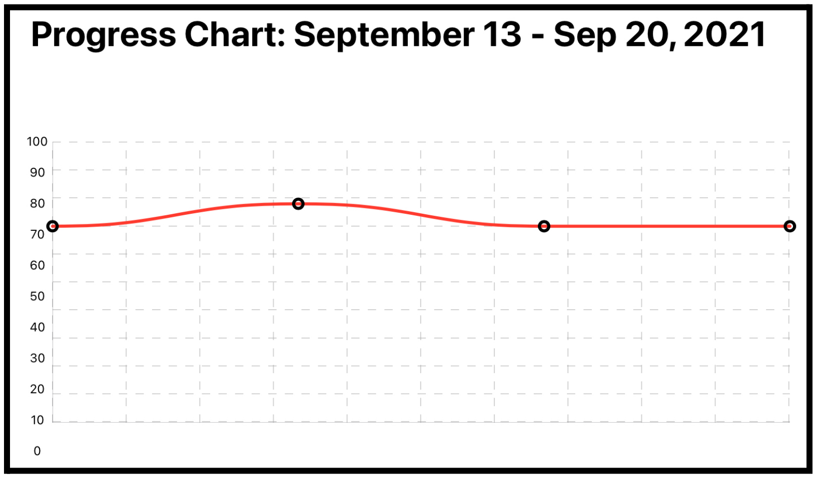
> Researcher Okay, so is it usually you who is taking (photos)? Or is it someone else who you asked to take?
> Zihao: Ahh I think it is mostly me, because they (my groupmates) don't really know what to do so they refer to me more.
> Researcher: Oh, like your teammates don't know what photos to take?
> Zihao: They don't know how to take photos; they don't know how to go into the app.
> Researcher: Alright. So you're the documentation leader, because they think you can use the app best?
> Zihao: Yeah.

Concerning reliance on peers, Zihao hardly consulted his groupmates about documentation. He took photographs of his groupmates without much communication, then he rated his group using the CoCreator App's confidence level scale based on his own consideration:

> Researcher: (point to a screenshare of Zihao's confidence level chart on the CoCreator App, Figure 4 below) How did you score 70-something? 80? A bit lower than 70? What did you have in mind that you rated those scores?
> Zihao: In our group, we mostly succeeded (achieving) the aim that we wanted.
> Researcher: And to you, what is the difference between 100 / 70 / 50 (on the confidence slider)?
> Zihao: Because some of them were playing and then I didn't want to let them play. But they keep on playing. **So, if they can do more work, (the score) will be better (higher).**
> Researcher: I see. So you took into account your group dynamics, like whether people were focused or not?
> Zihao: Ya.
> Researcher: Okay, were there any points in time where it was more of like, "I feel confident about this step, therefore, it's a higher rating", or it's more of you looking at your group's (confidence)?
> Zihao: Looking at my group.

In this excerpt, it may be interpreted that Zihao perceived the confidence level tracker as a scoring or grading mechanism, as he approached it from the perspective of how effectively work was completed within the group - "So, if they can do more work, (the score) will be better (higher)." Figure 12 below shows Zihao's group's progress chart based on his scores during one class session.

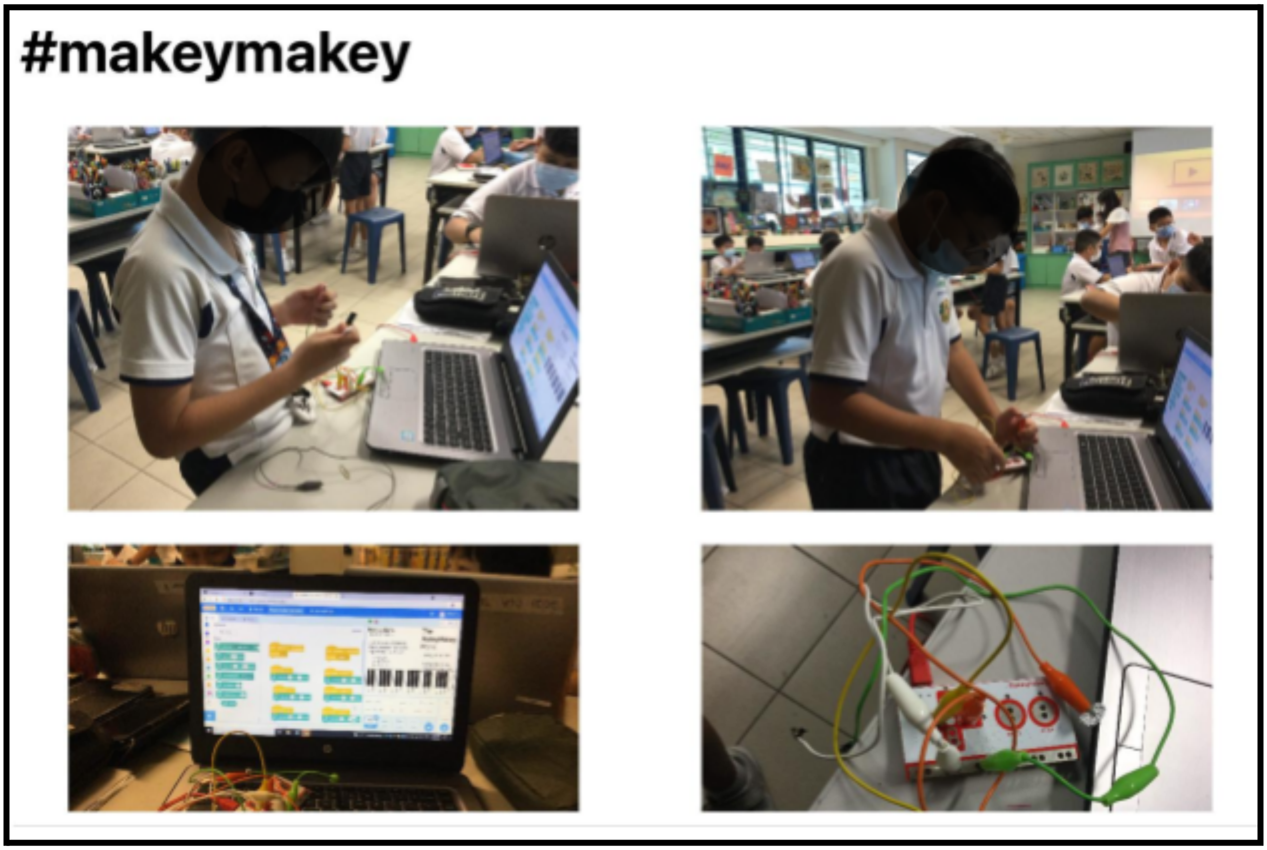
Figure 12 *Zihao's group's weekly progress chart visualization*



In terms of reliance on the teachers, Zihao needed occasional reminders from the teachers to do his documentation. Zihao mentioned in his interview that he would document instances when his groupmates are in the process of making and after the product or task is complete, but he forgot to document instances of discussion:

> Researcher: What kinds of photographs will you take? Would you take a photo when your team is doing something that's very successful, or maybe your team got into a bit of an argument?
> Zihao: We take photos when we're doing the project (in Figure 13 below). One of us takes the photo of us doing (making). Then, when we were discussing, we didn't take photos, but then in the end we did take photos.
> Researcher: You took photos of your end product?
> Zihao: Yeah, the end product.
> Researcher: During discussion, why did you decide not to take (photographs)? Or did you just forget to (record)?
> Zihao: Uhhhh. Forget.

Figure 13 *Zihao's photographs of his group's making process and hashtags he used*[5]



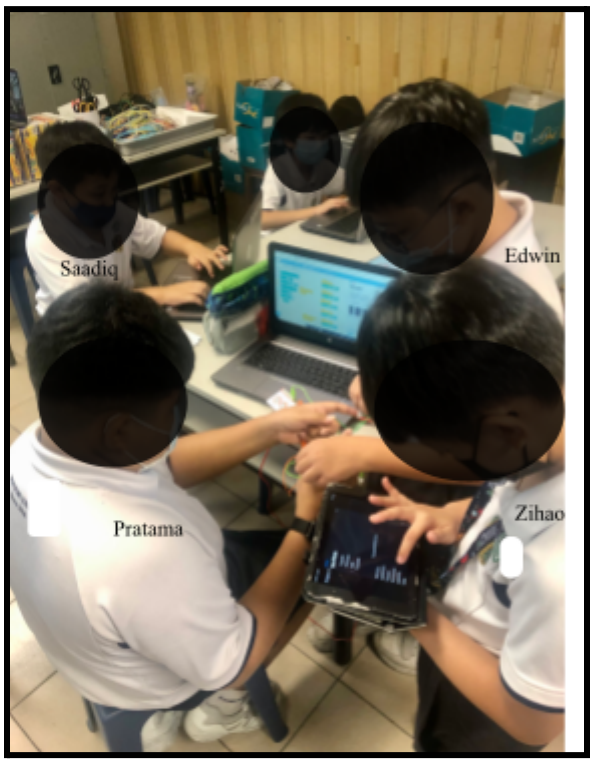
[5] Students' faces have been darkened and blurred to protect minors' identities, as requested by Singapore's Ministry of Education.

Regarding value of documentation, Zihao had an end goal to collect photographs of his groupmates "in action" - he stated that he and his group wanted to view their construction journey:

> Researcher: I see. So when you mentioned just now, you take photos at the start, in the middle, at the end. Is it usually because your teacher told you / reminded you the other day? Or is it that you wanted (to do the documentation)?
> Zihao: I think it's more like our team because we actually want to see our progress.
> Researcher: I see. What kind of progress do you want to see?
> Zihao: Like, **at the end, we got the MakeyMakey project, then we actually look back at what we did (over the past weeks).**

Because Zihao took the lead on documentation and hardly consulted his groupmates about their ideas and opinions, his groupmates minimally participated in reflecting on their activities in class. I observed that Zihao would pick up the iPad every ten to fifteen minutes, take a couple of photographs of his groupmates' current work, and log into the CoCreator App to create a post right next to his groupmates (in Figure 14 below). However, Zihao hardly communicated with them about what he was posting, and his groupmates did not let Zihao know about challenges or successes to record in the CoCreator App either.

Figure 14 *Zihao documents as his groupmates code on Scratch and connect the MakeyMakey microcontroller*



Later, when I interviewed Zihao's groupmate Pratama, Pratama stated that he had questions related to coding, but he hardly voiced these questions and he felt that he did not work well with his groupmates. Rather, I observed that Pratama chose to tinker with Scratch or MakeyMakey until he solved them on his own:

> Pratama: I can understand most of the programming but sometimes I mess up the program.
>
> …

Pratama: I don't really work together with the others. Mostly I prefer doing my work on my own. I'm not that good with more than one person. (In my group,) I'm not really in charge of anything.

The "Follower." Deepak's group had two documentation leaders - himself and Dara - and he was one of them. He is an example of a student who adopts the "follower" persona. On the criteria of style of documentation and reliance on peers, Deepak stated that he mainly followed Ivan's (his groupmate) instructions on photographs to take during making sessions, and these would be photographs of instances when Ivan or the group is able to complete a task successfully:

Researcher: Can you tell me more about how you choose what photos to take of your group?

Deepak: Ivan (Deepak's groupmate) told me what to take.

Researcher: Like, you let who tell you what to take?

Deepak: Ivan.

Researcher: Okay Ivan tells you what (photos) to take. And did you listen to him? Or did you say, "No, I want to take (a photo of) something else."

Deepak: Yeah, I listen to him.

Researcher: Okay, why? Can you give me an example of what (photos) he asked you to take?

Deepak: **When he connected all those alligator cables, he will ask me to take a picture.**

Researcher: And why do you think he told you to take a picture of the alligator cables?

Deepak: **Because he is able to connect it** and we're done.

Cross-referencing Deepak's interview with observations of Deepak's group, I noticed that Ivan and Sahil (another groupmate) are typically the students who instructed others on division of labor and artifacts to document, and Deepak and Dara would go with the flow. Figure 15 below shows an instance when Ivan was looking over Deepak's shoulder, Sahil was speaking about what he was making, and Deepak documented components of their musical instrument that his groupmates made out of art and recycled materials.

Figure 15 *Deepak documents his group's activities, with Ivan's input*

A few seconds before, Ivan brought over the red cardboard box and started assembling the MakeyMakey microcontroller in it (this would serve as the musical instrument's interior electronics). Deepak picked up the iPad and logged into the CoCreator App to take a quick photograph of the red cardboard box with the MakeyMakey microcontroller, before Sahil told Deepak to assist with making clay models. Deepak put down the iPad and switched to making clay models immediately. It was not apparent in this observation whether Deepak completed a post on the CoCreator App (completion of a post equates to completing hashtags and self-reporting the confidence level score). However, I noted that this sequence of actions and communication happened quickly, over less than a minute. On including confidence level scores, Deepak enacted in his interview that he would ask Ivan whether he could upload a photograph of him (Ivan) or his work onto the CoCreator App, and what score Ivan would like to report for that particular post:

> Researcher: If you were taking a photo of Ivan - do you ask him like "how confident are you that you did this correctly?"
> Deepak: Yeah, I'd ask him first.
> Researcher: Oh, you asked him. How's the conversation like?
> Deepak: I say like "Ivan, can I upload onto the app?" Then he say, "Oh okay I am confident." "How confident?" "90%"
> Researcher: Oh so he'll tell you the number just like that.
> Deepak: Yeah.

I observed another instance of documentation in Deepak's group, this time led by his group's other documentation leader Dara. Dara took a photograph of Ivan while Ivan was molding a chicken drumstick out of clay, but not paying attention to Dara (photograph on the left in Figure 16 below). Ivan then realized that Dara was taking photographs of him, then instructed Dara to take another photograph of him, this time with him presenting his clay chicken drumstick (photograph on the right in Figure 16 below).

Figure 16 *Dara documents Ivan's activities, then is redirected by Ivan*

Deepak explained in his interview that they (he and Dara) would take photographs of groupmates who looked confident in their work, because he was afraid of retaliation if he posted a photograph that his groupmates were unhappy with:

> Researcher: Why might you like to take photos of people who seem more confident about their work?
> Deepak: **Because when I upload and then they find out, the people who are not confident will scold me.**
> Researcher: Oh, they will scold you?
> Deepak: Yeah.
> Researcher: I see. Have they scolded you before?
> Deepak: No.
> Researcher: But you think they will scold you?
> Deepak: Yeah.
> Researcher: Something like "why did you take a photo of me? I wasn't even doing it properly!"
> Deepak: Yeah.
> Researcher: Okay, so this is all in your thoughts? You actually haven't been scolded by a friend. Right?
> Deepak: Yeah.

Deepak rationalized that he would document moments where students looked confident when engaging in their activities, and that he would not document moments where students were lost or uncertain about their steps, which had been the case several times with Ivan and other students in his group. For me as a researcher, this is interesting to note, because Deepak perceived his groupmates' uncertainty or errors as negative moments that may trigger a personal attack on himself. This also suggests that Deepak perceives documentation as showing only the best work. This perception is not uncommon; I had also observed in previous studies on K-12 students' documentation that students were more inclined to take photographs of only their final product or aesthetically pleasing aspects of their work-in-progress prototypes (Chan & Holbert, 2019).

Lastly, on reliance on teachers, Deepak listened to reminders from his teachers when they reminded the entire class about documentation. However, because his groupmates occasionally mentioned documentation while they were working on individual components, or asked him or Dara to take photographs at intermittent periods, Deepak received many more reminders about documentation from his peers than teachers about documentation.

The "Diplomat." Kian Tat was his group's documentation leader, and embodied a "diplomat" persona. On style of documentation, he took greater agency than Deepak over documenting his group's making processes. This excerpt below shows that Kian Tat takes into account his groupmates' opinions and thoughts around the making and documentation process before documenting, as he explained a situation when he decided not to document an incident of disagreement that occurred within his group. Kian Tat suggested that his groupmates may tackle him physically if he documented the incident, and that he would rather follow his groupmates' opinions on deciding which artifacts or activities were important to document:

> Researcher: Did you take a photo of that incident (disagreement / argument during making)?
> Kian Tat: Nooo!
> Researcher: Why not?
> Kian Tat: Because I don't want to… I don't want to take pictures, because it's very bad to take pictures. So I don't take.
> Researcher: It's bad to take a picture of the argument?
> Kian Tat: Yeah, **I know that I should stop them, but if I stopped them, someone will bash me. Or they'll scold me.**
> Researcher: So you didn't want to get involved in the argument?
> Kian Tat: Yeah.
> Researcher: So you just don't take pictures and don't say anything.
> Kian Tat: Yes.
> …
> Kian Tat: You see, if I take a picture of the whole argument right, they (my groupmates) will be asking me, **"Why did you take a picture? This is not the important part!" They will ask me like that.**
> Researcher: I see - so your friends think it is not important.
> Kian Tat: Yeah. So… I think, I better not take (a photo of arguments or discussion).

Kian Tat associated third-party documentation as participation in an argument or discussion that he did not want to be involved in, thus we made a conscious decision not to document a disagreement that his peers may perceive to be negative down the road. When prompted further about reframing the argument / disagreement into a form of discussion, Kian Tat gave another explanation about why he would not record this anyway, now due to the nature of the topic (type of object to build), but returning to the point that his groupmates would be upset if he had taken photographs of "unimportant parts" of the project:

> Researcher: Okay, but what if the argument was reframed as a discussion? Like you're just throwing around ideas.
> Kian Tat: Once we did that.
> Researcher: And did it work better? Or did people still disagree with each other?
> Kian Tat: Um, it was good - it's a bit better. When we were making the cat on a car, we were deciding what color for it, and then one of my teammates suggested the cat to be orange and white. And then I tried to build a car, but it looked more like a sausage than a car.
> Researcher: So did your teammate get angry about that?
> Kian Tat: No. They just stared at me and said, "This is wrong. I teach you how to make it better."
> Researcher: And did you capture any of that in terms of a picture or like writing in your sketchbook?
> Kian Tat: No.
> Researcher: Why not?
> Kian Tat: It's not important to record because we can choose other (objects / ideas) instead of a car.

As for reliance on peers, Kian Tat did not depend directly on his groupmates for instructions on what and how to document; rather, he led by documenting what he thought would be important for the group, judged by his observations. He described how he reported his group's confidence level on the CoCreator App, based on observing his groupmates' expression, not direct communication:

> Kian Tat: Since this project is fun, I mostly use the (confidence) level 100.
> Researcher: Okay, so you based it (self-reporting) on fun and enjoyability? Do you check with your teammates about how they felt?
> Kian Tat: **Based on their expression, I can tell they are happy.**

On reliance on teachers, like the other students, Kian Tat would receive occasional reminders about documentation from his teachers, but he is mostly proactive on his own when he documents. However, on the value of documentation, he figured saving what he did during this maker program "could be useful in the future," but he was not clear specifically as to why and how documentation could be useful to him or his team.

Feedback. Feedback is regarded as a primary component of formative assessment (Black & Wiliam, 1998), where the intention is to communicate new information to the learner to modify his/her thinking to improve learning (Shute, 2008). Using Hattie & Timperley's definition, feedback is information provided by an agent (such as a person, experience, or self) regarding aspects of one's performance or understanding, a "consequence" of performance in a spectrum from instruction to feedback (2007). For feedback to be helpful, the provider needs to take into account the many ways learners might interpret feedback, and characteristics like timing and how information is delivered (Havnes, Smith, Dysthe & Ludvigsen, 2012). In maker education, a particular form of project-based learning where students are tasked with using a variety of traditional and highly technical tools to create physical artifacts, feedback is vital to ensure students progress down a productive path. The following examples in this section show teachers providing students with feedback synchronously in class and asynchronously through the CoCreator App, where students document their project work by uploading photographs they had taken in class and self-reporting confidence scores for specific tasks.

In Hattie and Timperley's (2007) systematic review of literature on feedback processes, they identified four main types of feedback students typically receive: *Task Feedback*, *Process Feedback*, *Self-Regulation Feedback*, and *Praise/Self Feedback*. Task feedback provides students with information about whether their work is correctly executed or not; Process feedback encourages deeper reflection on the extent of success to which a task was done and areas for improvement; Self-Regulation Feedback challenges students to self-assess their work and develop self-directed learning skills; Praise/Self Feedback focuses more on the student rather than the task at-hand, and may not necessarily encourage students to invest more effort in a task (Van Boekel, Weisen & Hufnagle, 2021; Hattie and Timperley, 2007). I used Hattie and Timperley's categories to identify instances of synchronous and asynchronous feedback that I observe.

First, I tallied the types of asynchronous feedback I observed from the CoCreator App. Overall, there were 10 occurrences of asynchronous feedback - two of which were task feedback, zero process feedback, one self-regulating feedback, and seven praise/self feedback. The total number of asynchronous feedback occurrences paled in comparison to the total number of synchronous in-class feedback (estimated 100+ occurrences) across five observation sessions. On average, both Mr Tan and Mrs Lee individually rotated to each of the five student groups at least twice during each class to provide feedback. This means each group received at least four instances of synchronous feedback in one class, and over the five observation sessions, each group will have received at least 20 instances of synchronous feedback, totaling to 100+ expected occurrences overall. During each weekly class, I observed at least one out of five groups. For synchronous sessions that I observed in detail with fieldnotes, task feedback occurred overall eighteen times, process feedback five times, self-regulation feedback once, and self/praise feedback three times (although one of which was criticism, not praise). Task feedback occurrences were in the majority, and task and process feedback mostly intersected with the sub-codes checking in or troubleshooting. Synchronous self-regulating feedback happened the least number of times overall, and the particular instance I observed intersected with "Encouraging", where the educator told a group of past emotional challenges that a student group from last year had faced. Two instances of self/praise feedback intersected with encouraging because the educators praised students for completing a certain stage of their project; the third instance of self/praise feedback intersected with troubleshooting as the educators realized students ran into issues in their project, not because they did not understand a task, but because they executed the task in a lackadaisical manner (as perceived by the educators). Below are examples that highlight the various types of feedback and interactions.

"Teacher Moves" supported in Synchronous Feedback. This case explores feedback given from a teacher to students in an in-person maker classroom where both asynchronous and synchronous modes are available. For asynchronous feedback, the most prevalent codes are praise/self feedback + encouraging. For synchronous feedback, they are task feedback + troubleshooting (an example shown in the quote from Mr Tan). Deepak's group (Group B) had interviewed the school's security guard and noted that his preferences and hobbies are: chicken rice (a local dish), Shih Tzu dogs, the color blue, and soccer. The students wanted to create a musical instrument that represented at least one of his preferences, but were indecisive. Upon noticing that Group B had rather disparate ideas and had not settled on a direction to start making, Mr Tan strongly emphasized the importance of time management and brainstorming feasible ideas with repeated phrases (left out in the quote due to space constraints), which I classified as task feedback. He stood at the group's table where Deepak and his four other groupmates were seated around it, and verbally highlighted a few points:

> If the project is going to be chicken rice, how are you going to make chicken rice look like chicken rice? … Think about it; don't throw out ideas blindly without thinking about the processes ahead! … If at the end you know you are going to struggle to make a physical product, then that idea I would think - don't even consider it because you need to think ahead, because you don't have time.

After Mr Tan left this group, while searching for images of chicken rice made of clay, the students stumbled on an aesthetic image of *nasi lemak* (a different local rice dish but with some similar ingredients as in chicken rice) made of clay. They latched onto this new idea to create nasi lemak instead of chicken rice, and started assigning amongst themselves on items to create. In class upon noticing this sudden change, Mr Tan prompted the students: "So now you're making nasi lemak (a Singaporean Malay rice dish) instead of chicken rice (a Singaporean Chinese rice dish)?" Mr Tan used a surprised questioning tone, raised his eyebrows and widened his eyes, and looked around the table to gauge students' reactions. Mr Tan used a questioning tone, rather than an instructional tone, which made his hint more subtle when delivered in-person, instead of through asynchronous feedback (text) if it were written on the CoCreator App. Out of the students' earshot, Mr Tan let me know:

> (Group B) might not pass their project because they've missed the objective, which is to create a sculpture in line with the user's preferences, not a random thing they thought of suddenly. But don't tell them! I want to see how this all turns out, and let this be a teaching moment for this group and the entire class about the Design Thinking step Empathize.

This task feedback + troubleshooting about the rice dish did not surface in asynchronous feedback on the CoCreator App. Rather, on the CoCreator App, Mr Tan commented with a message that responded to the comments the student documentation leader had written, and I classified this as praise/self feedback + encouraging. This comment was a response to Deepak's comments about various tasks that each student is doing, and the relatively high self-reported confidence scores (70-80 out of 100) from the group throughout the lesson.

> Documentation Leader Deepak recorded the comments below on his group's work:
> 9/21 9:38am Dara made veggie from green clay
> 9/21 9:38am Dara said make Bandung with pink clay. Ivan made the white cup for bandung
> 9/21 9:39am Sahil wrote chicken rice idea and presented
> 9/21 9:39am Aaron made the egg and yolk from white and yellow clay
>
> Mr Tan commented a few days later:
> 9/24 10:19am Good to see everyone contributing to the project in different ways!

In this example, Mr Tan used synchronous feedback to provide detailed process-related suggestions for all groups and to offer immediate help when students ran into difficulty, whereas he used asynchronous feedback mainly for encouragement. Mr Tan mostly used the CoCreator

App to check students' work briefly and provide simple feedback, leaving more detailed feedback for synchronous time in class. During a post-implementation interview, he indicated that he worried asynchronous feedback might not be noticed by students as they are only able to use the CoCreator App when using the school's iPads during their once-a-week class sessions. Results may be different if the teachers allotted more time to provide various kinds of feedback on the CoCreator App, and if the teachers structured the in-person session for students to review feedback they received through the CoCreator App.

Extracting New Information from Asynchronous Feedback. Different from the previous example, the teacher Mr Tan here discerns new information about Group A and C students' progress and understanding of concepts through their documentation, comments, and self-reported confidence levels. Keeping in mind that self-reported confidence levels are subjective scores, I did not compare students' scores with one another, but I did compare how students rate their confidence levels multiple times during the same class period, or across different weeks.

Group A was generally on-task in class and completed their coding portions swiftly. As a checkpoint, the teachers instructed students to check in with them before proceeding to work on the portion with the MakeyMakey. Below is an extract of my fieldnotes:

> When Mr Tan checked that Group A had completed coding their musical chords on Scratch correctly, he signaled to the group to follow him to the corner where MakeyMakey microcontrollers were kept in the classroom. He prompted them "You know the difference?", holding up a couple of alligator clips. He instructed them to collect the wires and microcontrollers and move on to the next step to connect their Scratch code to the MakeyMakey. This interaction lasted nearly one minute.

During my interview with Mr Tan, he stated that he noticed the students lowered their confidence score from 100 to 50 in the same lesson with no written comments from the student, thus he felt that there could have been an unresolved issue from the class. However, Mr Tan was unaware that Group A students still felt somewhat uncertain about the coding assignment, because they had completed it successfully. Perhaps this was because the students did not voice out their questions directly to Mr Tan, and he checked for task completion, then moved them swiftly to the next stage. On the CoCreator App later, I noticed that Mr Tan wrote "Do approach me if the group needs more help" on a Group A student Pratama's post. I classified this as task feedback + checking in. Mr Tan noted in his interview that Pratama is typically conscientious and grasps new concepts well, but is soft-spoken and lacks confidence in the activities he does, which may have been a factor that led to a dip in self-reported scores.

I decided to obtain Pratama's perspective on this dip in confidence level scores during the same lesson. During my interview with Pratama, he explained that he still felt unsure about coding on Scratch although he seemed to have completed the assignment correctly in class, thus he chose to go with the flow when his group started the next stage that includes using the MakeyMakey, but decided to note his drop in confidence level on the CoCreator App. Here, Pratama's self-reporting and documentation on the CoCreator App provided Mr Tan an indication of his lack of confidence in the coding assignment that he did not feel comfortable articulating in class or in front of his groupmates - a separate avenue that could spark a follow-up conversation with Mr Tan. For Pratama's case, it does not matter if the teacher follows up with synchronous or asynchronous feedback, but it matters that the teacher was able to extract insights about Group B's uncertainty that would otherwise have gone unnoticed, even though Pratama or Group B was high-performing. After extracting these insights, the teacher can figure out their preferred mode of delivering the feedback, or further prompt Pratama or Group B for more information to clarify their uncertainty.

Group E's situation was slightly different from Group B's. For a particular session, I observed minimal synchronous educator feedback for Group E. Group E students completed the coding assignment in class, and asked each other within the group for help if one of them ran into issues.

> Colin, a student in Group E, recorded comments below on his work:
> 9/14 8:58am Coding the chords and changing the numbers were hard. I didn't understand what the chord numbers mean
> 9/14 9:01am It means that each number has a letter to make the chord. Which means that 48 is the letter C, 52 is the letter E and the number 55 is the letter G.
>
> Mr Tan commented a few days later:
> 9/17 10:17pm Do take note of the octave for your notes. Remember Mr Tan said notes 42-60? [Mr Tan wrote this on the school's learning management system, a different platform.] Check your codes if you have the time and identify the error.

Through the CoCreator App, Mr Tan noticed that Colin actually struggled with coding the musical notes during class, although Colin had not asked for help directly in class. This would not have been obvious in the synchronous session as Mr Tan would have assumed that the entire Group E had understood the concept and could move on to the next activity. I classified this piece of feedback as task feedback + troubleshooting.

To summarize Chapter 5, students working in groups have different documentation styles using the CoCreator App, affected by the level of collaboration within their group and the level of engagement of feedback students have with their educators. These different documentation styles (Leader / Follower / Diplomat) influence how students gain insights about skills or concepts in their projects, and how or whether they reflect on their processes.

The CoCreator App as a collaborative tool between the student and educator is only useful when both actively engage with the app's affordances around asynchronous feedback. However, as observed, synchronous feedback is still the "go-to" mode for educators during an in-person maker education class, and for students who are new to documentation. Students were still able to reflect and gain new knowledge through communicating with their teachers, but much of this was not facilitated through the CoCreator App, but through synchronous discussion instead.

Chapter 6: Discussion

This two-year design-based research study relies on qualitative data from interviews, observation sessions, field notes, and artifacts that students produced in order to provide insight into a technology-facilitated documentation processes for formative assessment in maker learning experiences. In this chapter, I highlight three key discussion points: 1) the importance of multimodality, 2) integration into routines and workflows, and 3) clear organization of artifacts to design a formative assessment tool that can assist elementary school students' learning and reflection in maker education. The last section of this discussion emphasizes the key role that teachers play in engaging with students' artifacts in order to facilitate productive reflection and feedback.

Bridging constructionist learning and metacognitive practices not only supports students in developing reflective practices as they engage and learn new concepts and skills while constructing artifacts to be shared with their peers and teachers, but also supports teachers in tracking students' progress and noticing any gaps in students' understanding. As the practices of making and documenting are integrated gradually into their larger building and collaboration process, students continuously form connections amongst topics, skills, and concepts they are familiar and unfamiliar with.

I revisit scholarly work and my iterative design process of the CoCreator App discussed in Chapters 2 and 3, and I review findings from the first and second implementations of the CoCreator App illustrated in Chapters 4 and 5 respectively. My aim is to consolidate the literature, design process, and implementations to refine how we can use complementary connections between Constructionism and Metacognition, so that this will be useful for future designers, researchers, and practitioners in developing student-driven formative assessment practices in interdisciplinary, technology-based settings.

The Importance of Multimodality in Documentation

Multimodality is a state that occurs when an artifact (an image or text etc.) has more than one mode of semiotic representation (Kress & van Leeuwen, 2001). This involves simultaneous or alternate use of more than one method of communication to send and receive information (Anastopoulou, Sharples & Baber, 2003). For example, presentation slides are now a common form of multimodal text in an educational setting, as slides combine text, oral presentation, visual typography, and illustrations with color and formatting (Hung, Chiu, & Yeh, 2013). Closely related to multimodality are the affordances of materials and communication media that impact learning. These affordances influence how this learning is externalized, which then impacts formative assessment.

We see from Phases 1 and 2 that students choose different types of modalities of documentation that they are familiar with. In Phase 1, students had different ideas regarding the type of documentation they would use - from photographs, videos, hand-drawn sketches, to bullet points (ranging from visual, audio, tactile forms of documentation) - to delineate steps in their process. Some students followed through with their original ideas of documentation methods, but many students either disregarded or changed their minds once they started building. Next, in Phase 2's case study on students building bridge designs in their school's maker program, hand-drawn sketches were familiar to them, essential, and recommended by their teacher. On the other hand, in Phase 2's case study on Dan iterating on different designs of *Medimind*, we observe Dan not only drew sketches, but also consolidated online research by sharing website links and images of inspiring designs on the CoCreator App and wrote a word document in the form of a report. Students preferred a variety of modalities, and these preferences shifted throughout their maker process. Connecting this with cognitive affordances, the provision of choice increases students' intrinsic motivation and their situational interest in the task (D'Mello, 2013) because students feel more autonomous when they are able to choose (Katz & Assor, 2007). When students are motivated to document because they have the option of using and choosing amongst multiple modalities, students develop agency and autonomy in deciding how and what they would document. When deciding how and what to document, students reflect on their task at hand. This suggests tools designed to support documentation should allow for a diverse range of modality choices.

The integration of different modalities of documentation on a technological tool not only allows students to interact with it based on the tool's affordances, but also allows teachers to observe how students are interacting with the tool and sieve out insights from these observations. During the first implementation in Phase 2, Dan noted that the CoCreator App's original framework with only virtual post-it notes and connecting arrows lacked space when he wanted to show more depth in his design and background research, so he explored other features to include a wider variety of documentation. Some familiarity with these other forms of documentation (he had previously shared website links, report-style word documents, images and screenshots in other school projects) helped Dan navigate the CoCreator App to add multiple modalities of documentation. In turn, by reviewing these different forms of documentation and engaging further through asynchronous comments and in-person prompting during check-in sessions, Dan's mentor was able to follow Dan's train of thought throughout his brainstorming and design process. From Dan's case, we learn that having the choice for modality of documentation is essential, and that having a choice to use multiple modes of documentation is highly crucial. Dan has been involved in the complex work of processing information (Jewitt, 2003), starting with the multimodal resources that are available to him and on the CoCreator App, then moving to modal responses that he thought would help him communicate his ideas best.

However, in Phase 2, although Brendan and Iman had less variance in modality of documentation, their teacher was still able to follow their train of thought by reviewing their hand-drawn sketches. Brendan, Iman and their teacher communicated ideas with one another about how they could strengthen the bridge by adjusting the placement of ice-cream sticks. Their teacher used visuals by drawing, because it was a mode that he and the students were familiar with, and it added additional insight to previous sketches that the students had drawn. The students then communicated ideas on editing their bridge using other sketches, incorporating their teacher's point about placement of ice-cream sticks. In this example, although Brendan and Iman chose to use one main modality - hand-drawn sketches - instead of Dan's use of multimodal documentation, they were still able to communicate their ideas, misconceptions, and understanding to their teacher. From Brendan and Iman's case, we see that the students learn best when they make sense of how they combine the modalities of documentation that they choose (Jewitt, 2003), and when they construct artifacts in their chosen modality that communicates their ideas to their teacher.

Integrating with Routines and Workflows

This discussion also brings us to broader questions: Do we need to document in makerspaces? If yes, what do we need to document? What is the role of documentation in maker education, moving forward?

Eluded in the previous section, when students document, they create artifacts of their work, and in doing so, create their own representations of what they understand of their work, externalized in the form of media and text. In the process of creating artifacts and hence representations, students undergo the process of inquiry, whether individually or collaboratively (with their groupmates) to figure out what and how to document. From a cognitive viewpoint, this documentation process enables students to be aware of their own thinking, a capability that Piaget classified as one of the defining characteristics of the most advanced stages of cognitive development (1976).

While the choice of multiple modalities of documentation is inviting and has cognitive affordances for students to reflect using different artifacts, we need to integrate multimodality with routine and materials that students are already familiar with. Documentation is challenging when it is not cultivated into one's workflow. For elementary school students, they may not consider the value of documentation in long-term maker education projects. For some students, they notice in hindsight after their project is complete that they should have documented more systematically, or at all. Pausing to document mid-way through an activity causes the student to step out of their activity, which oftentimes is viewed as disruptive, particularly when the student is highly motivated to complete their activity.

However, this dissertation argues that these pauses for documentation are very much needed because they serve as moments for reflection, recall, communication and/or feedback, which are key components to both constructionist pedagogy and metacognitive practices. I acknowledge that there is tension between the friction of initiating reflection during an activity and the integration into routine to ensure documentation happens. For these “interruptive” pauses to be productive and student-driven, we have to design documentation workflows that integrate with students’ routines, so that students are motivated to document and see the tangible value of documentation. A routine is regarded as a habitual process that one does frequently. When documentation fits into a student’s routine in a maker project, it becomes part and parcel of their making process, and they may gradually feel that documentation is less of a chore but more of a step that aids them. Similarly, when student-driven documentation fits into an teacher's pedagogical routine towards a learning goal (not a program evaluation or accountability goal), the teacher would use documentation as a means of engagement and communication with their students, and in doing so, influence their students to make documentation a part of their maker project routine.

We see in Dan’s example that he chose to integrate notes on his maker project with his personal to-do list, because he knew that he would check his to-do list frequently and it was easily accessible on his mobile smartphone. This to-do list was not part of the CoCreator App, but Dan’s note-taking on his to-do list was a behavior related to documentation. This gives rise to the question: how could we design documentation tools that integrate seamlessly into students’ workflows, so that students do not feel that they are completely stepping out of their activity?

This dissertation, although conducted in the context of Singapore, has provided design recommendations that can serve wider populations of students and teachers beyond Singapore. To extend this work further and personalize the design of documentation tools for students and teachers, one idea is to co-create documentation tools with students and teachers in their classroom context directly. By sieving out the most important aspects students value about documentation, choice of modalities, and current workflows they are acquainted with, and by identifying teachers' approaches and mindset towards documentation, we will find ourselves a step closer to cultivating a culture of documentation that works for a particular classroom.

Another way to integrate routine and workflows is to take a landscape scan of any artifacts that students already document (perhaps from other subject areas or classes), and of any workflows that students and teachers are somewhat familiar with, then incorporate a formative assessment system that consolidates these practices that already exist in the classroom, so as not to completely reinvent the wheel. For example, in the schools' contexts for Phases 2 and 3, students and teachers already use existing tools such as the Student Learning Space (SLS; a learning management system that Singapore's Ministry of Education developed) or Seesaw (a commercial mobile application that allows parents and teachers to view students' work in school). However, there are improvements that can be made to these tools to support student-driven formative assessment (documentation and reflection). My past research demonstrated challenges where Seesaw's features were minimally integrated into classroom culture and practices (Chan & Holbert, 2020) - although teachers actively reminded students to use the tool, students were more concerned about showcasing aesthetic final products instead of focusing on successes and challenges in their processes.

Features of the CoCreator App can be integrated into existing tools such as SLS and Seesaw to inculcate process-oriented formative assessment that prioritizes student-driven documentation and reflection. For example, hashtags as a method for artifact organization may help students quickly identify content and sentiments that they want to highlight from their artifact, and simultaneously help teachers review students' grasp of specific topics or skills. The visualization of confidence levels towards maker tasks is a form of documentation that encourages students to express and externalize their emotions while engaged in a specific task. These are all data points that provide teachers with information and potential areas for follow-up that they may not always gain from solely synchronous in-class interaction with a crowd of students. Later in the conclusion, I also indicate my continued interest in working with government agencies in Singapore to follow up on how features of the CoCreator App can be integrated into the SLS, to work towards developing useful formative assessment tools.

My observations of students' interactions with a formative assessment tool have added additional empirical support to arguments regarding the important role that metacognition plays in students' cognitive development. Aligned with previous work in metacognition, my study illustrates that enabling students to develop metacognitive expertise through documentation plays an essential role in facilitating interdisciplinary learning on their own, within their group (with peers), and with their teachers. A contribution to the theories of metacognition and cognition is that my dissertation acknowledges the social processes that complement metacognitive processes, ties in the aspect of constructionist pedagogy that promotes sharing and learning with others in the environment, and puts forth practical recommendations on assimilating workflows to enhance development of metacognitive expertise during documentation.

Organization to Achieve Routine with Multimodality

Students' and teachers' routines may not always coincide with multimodal choices of documentation. Another challenge we should consider when designing features that integrate with students' routines is the balance between routine and multimodality. How might we create a documentation tool that fits within students' workflows, yet accommodates their choices, so that they see value in documentation? From Phase 2, for several students, I observed that students may have had too many modalities of documentation, resulting in a lack of systematic organization of artifacts. All students started documentation with the CoCreator App, but eventually branched out to use their own chosen documentation methods during prototyping. For example, Dan used his personal to-do list on WhatsApp, sent code snippets on Slack, and maintained a collection of photographs, sketches, and word documents on the CoCreator App. Another student Damian recorded his experiments on a (hard copy) booklet, along with sketches on looseleaf sheets of paper, while the group of three students (Russell, Jasim, Harjit) faced difficulties communicating with one another because they each chose to use different modalities of documentation. Additionally, the holiday program organizers also introduced templates on Google Slides and Prezi to the students as documentation platforms that they could use for their final showcase.

Although there are many choices of modalities of documentation, having documentation on too many platforms in an unsystematic manner certainly does not work well within the students' workflows. Instead, it confused them and led to miscommunication or lack of communication. Within groupmates who used different modalities, students were confused as to where, how and what each other were documenting. If students cannot properly organize and communicate their documentation, this hinders their reflection (our goal). Similarly, if teachers are unable to organize students' artifacts and reflections, this may lead to inaccurate interpretation of students' understanding and progress. We have to strike a balance between introducing modalities of documentation students are unfamiliar with and need to learn, and modalities that students are familiar with and already use as part of their routine.

The CoCreator App (mobile version) in Phase 3 aimed to tackle this issue by structuring a documentation process primarily using three key modalities of documentation - hashtags, photographs and text for captions and reflection - with an added hashtag feature to assist students in organizing their artifacts. Students drew hand-sketches and wrote notes on their paper booklet too, then took photographs of these sketches and notes to upload onto the CoCreator App. While students were more restricted in their choice of modalities of documentation here, the process of documenting was more integrated into their brainstorming and prototyping workflows. The step-by-step process of taking then uploading a photo, selecting hashtags, self-reporting a confidence score, coupled with the ease of picking up a mobile tablet to use the CoCreator App, significantly lowered the barrier of entry during a hectic making session. Nevertheless, students still needed documentation reminders and facilitation from their teachers, because documentation itself was a fairly new practice to the students in any of their classes at school. This highlights the importance of teachers' facilitation methods in nurturing a culture around formative assessment and a routine embracing documentation, discussed in the next section.

Teachers' Engagement and Facilitation in Students' Documentation Processes

While we strive for student-driven documentation and formative assessment, the role of the teacher is critical and cannot be ignored. Teachers' perception of formative assessment, engagement with students' artifacts, and facilitation of students' documentation processes all influence what, how and why students document, in order for students to achieve productive reflection, which equates to opportunities for learning. I would like to draw our attention to a keyword in the dissertation's second research question: *collaboration*.

In Phase 3, we observed two different attitudes and approaches towards student-driven documentation in Mr Tan and Mrs Lee. While both teachers verbally supported formative assessment through asynchronous feedback and documentation, Mr Tan and Mrs Lee's levels of engagement with students' artifacts were opposite. Mr Tan periodically checked through the CoCreator App to provide asynchronous feedback, while Mrs Lee hardly touched the CoCreator App although she constantly reminded students in class to upload their photographs onto it. This difference in behavior between Mr Tan and Mrs Lee may have sent mixed signals to the students in how they perceived the importance of the students' artifacts. Mr Tan reviewed students' documentation weekly, but stated that he was more comfortable with synchronous feedback as compared to in-app asynchronous feedback, because students react more quickly to his comments when he provides them in real time. Although Mr Tan compared synchronous versus in-app asynchronous feedback in this manner, I would like to note that student documentation on the CoCreator App was not made to remove in-person synchronous feedback, rather, it was intended to augment teachers' engagement with students' procedural artifacts.

On the other hand, in her interview, Mrs Lee stated that she was "hands-off" in her engagement with students' documentation, because she felt that it was something that they would refer to much later, perhaps in the next academic year when they engage in their next maker project. Mrs Lee perceived that the value of documentation comes in the longer term when students are using it for recall, or potentially for other teachers to view what students had covered in the past. Although long-term recall was not the primary intended purpose of the CoCreator App, from Mrs Lee's interview, I noted that teachers (particularly co-teachers of the same class) may have different mindsets towards formative assessment and documentation, thus it would have been helpful to discuss these approaches before embarking on the program, in order to inculcate best practices that will affect how and what students document.

Granted, there could be many other factors that caused this lack of engagement with students' artifacts - there were external logistical constraints that may have affected the teachers' level of engagement overall. As noted in Chapter 3: Methodology, my data collection phase occurred during a spike in COVID-19 cases in Singapore, and all teachers were highly vigilant towards frequent changes in public health guidelines and potential school closure.

Sociocultural Norms

The previous sections discussed extensively about integrating workflows and cultivating a classroom culture for documentation around the technological tool, so this leads us to ponder about sociocultural norms that may give rise to differences in workflows and cultures. How might all these shared practices impact what occurs in documentation? Also mentioned in previous chapters, makerspace cultures differ between informal and formal spaces, and space-to-space individually too. The topics and style of projects that elementary school students engage in are highly dependent on their teachers' expertise and backgrounds - for example, the school in Phase 2 approached making (building a bridge) from an engineering vantage as their teacher was previously a trained engineer, but the school in Phase 3 approached making (designing a musical instrument) from an artistic angle because maker education was part of students' formal art and music classes. There are already different documentation cultures embedded in engineering versus art and music, versus daily schoolwork that students engage in. Furthermore, the culture and practices around using tangible tools versus software tools may differ amongst makerspaces too. How might we synthesize these different cultures and practices to "make documentation work" for local contexts?

Documentation cultures that stem from engineering could integrate with and complement documentation cultures from art and music. For example, the use of portfolios originated in art education decades ago, but it has gradually been incorporated into many disciplines, such as medicine, teaching, design etc. The maker education community already comprises teachers and designers from a diverse range of backgrounds with knowledge-sharing and professional development networks, but there is still room to bridge and borrow assessment and documentation cultures from various disciplines to create local norms that work within a specific maker classroom. These local norms would be different from standards that may be implemented at a district or national level.

Chapter 7: Conclusion

In this final chapter, I summarize the contents of the previous chapters, then discuss my dissertation's limitations, contribution, and future work.

In Chapter 2, I drew on literature and prior work to illustrate the theoretical foundations that inform my dissertation, and presented the proposal to bridge the theories of Constructionism and Metacognition. In Chapter 3, I described the data collection and analysis methods I used in conducting this dissertation, and the iterative process I used to design the CoCreator App guided by the theories of Constructionism and Metacognition. In Chapters 4 and 5, I described the first and second implementations of the CoCreator App. The first implementation consisted of two phases - Phase 1 conducted online, Phase 2 conducted in an informal (afterschool) and formal (school) maker environment. The second implementation (Phase 3) was conducted in a formal maker environment at a school. I described how students in these maker education programs and classes documented their projects, either individually or in a group or both, and how these documentation artifacts supported student-teacher interactions related to feedback.

From Chapter 6, I delineate three important takeaways from my study on documentation in makerspaces:

1) Students need and want multimodal choices for documentation, as these modes have different affordances and representations of learning. However, these multimodal artifacts require systematic organization in the documentation process. Groupwork also entails communication about the various modalities of artifacts, so that all students are actively involved in reflecting on their tasks and outstanding questions or challenges they may still have.

2) We need to balance both multimodality and integration with routine. Routine can be nurtured not only through seamless use of a technological tool, but also through a classroom culture where students and teachers openly and often discuss the value of the artifacts that students document. At elementary school level, when students are new to documentation, students often still need their teachers' guidance on when, how and what to document. Forming this routine and a closer relationship with the documentation tool's affordances will foster a community that reflects together, provides constructive feedback to one another, and as a result learns together.
3) Engagement from teachers and mentors is key to successfully fostering a strong understanding of the value of documentation and reflection in elementary school students. While structure and guidance in a technology-facilitated documentation process assists students in reflecting on their own or with their groupmates, teachers and mentors need to be on the same page with co-teachers and/or co-mentors in terms of how they communicate with students about their reflections and artifacts. A teacher or mentor pointing out essential information that they gathered from students' documentation will demonstrate to students their engagement with the students' ongoing work, ideas, and questions. A disparity in communication and feedback between the student and teacher may lead students to perceive that documentation is less important or less helpful.

I return to the research questions that drove my dissertation. Here, I summarize the ways in which my study on a technology-facilitated documentation process addresses these questions, and exposes new questions for further research.

1. How might artifact documentation and organization, as a mode of formative assessment, provide new insights to students and teachers in complex making/construction processes?

For students, they could gain new insights about topics or concepts they are unfamiliar with, make sense of feelings they experience during making, and keep track of evolving ideas. For Brendan and Iman in Phase 2, they learned about the effects of material structure and positioning to strengthen their bridge through hand-drawn sketches that communicated their gaps in understanding to their teacher about material strength. For Dan in Phase 2, artifact documentation and organization helped him view fragments of information he had been collecting to brainstorm and develop ideas for his prototype. For Deepak's group in Phase 3, they documented pivots in their thought processes while they built with various materials and electronic components.

For teachers, students' artifacts provide a window into students' thoughts, ideas, struggles, and successes. In Phase 2, we saw that Brendan and Iman's teacher noticed their lack of understanding in material strength and component positioning through their drawings. With organization of their artifacts (drawings) over the course of the program, Brendan and Iman's teacher could track their bridge design's improvement, which demonstrates to him that they have at least grasped some rudimentary knowledge about the effect of adjustment of components' positions in a bridge to achieve greater strength. In Phase 3, with the CoCreator App's hashtags for each photograph (artifact), Mr Tan could figure out (to some extent) main points that students wanted to capture in their photographs. While most hashtags related to content in the photographs, a couple of hashtags related to feelings students experienced, and this could potentially be referenced with students' self-reported confidence level scores in the application.

2. How could artifact documentation embedded in a collaborative tool contribute to students' identification and reflection of new knowledge gained during their making process?

Students and teachers could collaborate on the CoCreator App to jointly figure out emergent ideas and next steps in the students' projects. In Phase 2, Dan's mentor, who studied Dan's documentation asynchronously before their check-in sessions, used Dan's artifacts to prompt Dan in ways that would be productive for his project, such as examining users' needs in more detail using primary and secondary research, identifying feasible materials that Dan could use, etc. Simultaneously, Dan used his artifacts to contemplate information he knew already and information that was new to him, from his mentor's feedback or from his own research. In Phase 3, we observed that Pratama had questions about coding that he felt uncertain about, yet uncomfortable asking his group or in class, but he documented this feeling as a self-reported drop in confidence level. Based on prior knowledge about Pratama's academic performance, his teacher Mr Tan noted that this was an unexpected drop in confidence level. On one end, Pratama reflected on this new knowledge (in the form of questions) that he gained through his coding activity in class, and on the other end, Mr Tan was able to locate a potential unresolved gap in understanding regarding the coding activity.

Limitations

There were several limitations in this dissertation. I observed that students and mentors in the informal makerspace used the CoCreator App more extensively than students and teachers in the formal schools, likely because the holiday maker program provided students and mentors a lot more time and space for brainstorming and tinkering. This freedom contrasts with fixed class periods in school that students and teachers had to adhere to, therefore their time spent with one another and/or with the CoCreator App was significantly less, which resulted in my observation of overall less engagement in documentation and feedback in the schools. Because the CoCreator App prototypes were studied in informal and formal learning sites that had rather different norms and contexts, my findings from these contexts are not entirely generalizable to all informal and formal learning sites. Many other factors also impacted how students and teachers used the CoCreator App prototypes amongst the three phases and sites. For example, some factors include: influences from Singapore's national education system, the format of how school was structured, the students' individual levels of familiarity with documentation and prior knowledge of formative assessment, self-selected versus teacher-selected (pre-determined) projects. While my findings do not provide sweeping claims about formative assessment implementation across the board, my findings do provide an illustration of how interactions related to formative assessment play out between elementary school students, between students and teachers, and the three-way interaction amongst student, teacher and tool.

Another huge limitation was the COVID-19 pandemic as I collected data over 2020 and 2021, the two years when circumstances were the most uncertain. This caused me to adapt my research methods continuously according to changing IRB guidelines and local public health guidelines. Phase 1's interviews and observations were conducted entirely online via video conferencing during the lockdown in 2020. Conducting observations online restricted my view of the students' surroundings, such as how they set up their smartphone cameras and other devices they used to document their work, what they were making with their hands, what materials they chose to use and how they used them, etc. Furthermore, as instructed by the IRB and Singapore's Ministry of Education, all my interviews with students and teachers (for all 3 phases) had to be conducted remotely through a video conference call, instead of in-person or on-site. I was not able to observe my interviewees' body language as closely as I intended to, and had to rely on their spoken content and tones.

While I was granted access to conduct in-person observations of students and teachers in Phases 2 and 3, the schedules of my research sites' maker education programs were also impacted by sudden home-based learning guidelines that the government implemented. For schools, the maker programs were suddenly compressed. In Phase 3, students unfortunately were not able to present their projects and do the final in-class reflection with each other that the teachers had planned. For the informal afterschool makerspace in Phase 2, the program became a protracted version with multiple breaks in between. This impacted my timeline for interviews and observations.

Due to aspects of qualitative research included in this design-based research study, another key limitation is my personal subjectivity and biases as a researcher. This may manifest in my assumptions, the prototype designs I created, and my perceptions. A related limitation is participant reactivity (Maxwell, 2008), whereby my participants who know me may have difficulty adjusting to my role as an observer or interviewer, or my participants (especially the students) may provide me with responses that they think I am looking for. Recognizing these limitations, I acknowledged in my research agenda since Chapter 1 where I stated my assumptions upfront, and ensured that my advisors and colleagues vetted my prototype designs and coding schemes for qualitative data analysis. To reduce the limitation of potential bias during data analysis, I removed all participants' names and coded the interviews and observations blindly, in order to decrease association of characteristics and material as much as possible to the participants. To address participant reactivity, I consciously reflected on how my actions and speech could influence participants, and verified my interview and observation protocols with my advisor and colleagues in advance of collecting data. I was also cognizant about creating an environment that is conducive for my research participants, both adults and children, to be honest and share openly.

The sample size was also restricted in this study, as I constrained my study to three different research sites. As stated earlier that generalizability is not an intended goal or outcome, I strove for transferability by documenting thick descriptions and rigorous triangulation of qualitative data. From each phase to the next, my sample of students and teachers were different. This was due to ongoing changing circumstances that I faced in participant recruitment. For Phase 2, I chose to work with both a school and an informal makerspace to figure out the similarities and differences in approaches to documentation using the same CoCreator App prototype. However, Phase 2 was conducted at the end of the year, and for the school, it was a post-examination activity that was closer to informal learning conducted during formal curriculum time. For Phase 3, I chose to work with a different school because I wanted this formal learning environment to have clear learning objectives from planned formal curricula. Therefore, this could be a limitation as I am working with new population samples for every stage of the DBR process.

Finally, if I had more time, I would have done one more implementation with an improved mobile CoCreator App design with the school from Phase 3, and with the informal makerspace from Phase 2. Engaging and collaborating with the same teachers from Phase 3 and the same mentors from Phase 2, with an improved CoCreator App design, will produce more opportunities to better nurture meaningful documentation practices amongst students.

Contribution

Through the development of versions of the CoCreator App, I expand notions of how, what, and why elementary school students document during interdisciplinary project-based learning. This dissertation holds significance in contributing to the learning sciences community, particularly in the fields of constructionism, cognitivism, and metacognition. This dissertation begins with a bird's eye view of formative assessment methods that exist, but highlights that we lack understanding of how we can nurture students to be drivers of their own learning through self-directed documentation and reflection.

The versions of the CoCreator App demonstrate my experiments with theoretical elements from Constructionism and Metacognition applied into design and technology, while my findings from observations and interviews with students and teachers / mentors elucidate successes and challenges of documentation in both informal and formal urban learning environments. This dissertation also contributes to diverse practices in the design-based research community. My study is an example of DBR conducted in an international context, adapted in Singapore's local context.

Towards Singapore's landscape and future of education: Singapore's Ministry of Education has launched the Applied Learning Programme (ALP) with plans to implement the program in all primary and secondary schools across the nation. ALP encourages students to apply concepts learnt in different core subjects to interdisciplinary experiential projects, and learn skills such as design thinking and computational and digital literacy. A growing number of K-12 schools in Singapore have makerspaces, and in my view, the spirit of ALP resonates with maker education and constructionist pedagogy. However, there are minimal formalized structures around assessment (both student-driven and teacher-facilitated) in ALP at the moment. I hope that my dissertation sheds light on documentation processes and practices that could be incorporated into assessment for ALP. Additionally, Singapore's Ministry of Education has also implemented the Student Learning Space (SLS), a nation-wide learning management system for all public schools. During the COVID-19 pandemic, SLS was essential for teachers in communicating with students via online learning. Now, SLS is very much incorporated into teachers' and students' workflows for most curricular subjects. I am optimistic that my development of versions of the CoCreator App can inform how formative assessment could be weaved and supported in the SLS. I would be thrilled to gain sandbox access to the SLS, and continue developing this work with Singapore's Ministry of Education. Singapore's Government Technology Agency (GovTech) also works on technology projects related to education - perhaps we can find synergy in figuring out design features that can amplify formative assessment for ALP and other interdisciplinary subjects through the SLS.

Future Work

The scope of this dissertation concentrates on the students' behaviors and perspectives towards documentation, reflection, and feedback, and also discusses teachers' engagement with students' artifacts and communication regarding feedback. However, during the interviews in Phases 2 and 3, students raised that there was a lack of opportunities to learn from peers or other groups working on different projects. For students who worked individually in Phase 2, they showed some curiosity about other students' projects, but they only really viewed each other's projects during the "demo day" showcase at the end of the program. For students who worked in groups in Phases 2 and 3, they had some opportunity in class to discuss their ideas with students from other groups, but they felt that they did not have enough time to properly understand their peers' projects, or receive constructive feedback from peers about their own projects. There could be ways to further enhance this synchronous discussion and potentially expand this discussion through technology asynchronously, via improved peer-to-peer collaborative designs on the CoCreator App.

One of my original intentions of exploring formative assessment in a maker learning environment was to explore how students and teachers could collaboratively figure out, via negotiation and discussion, appropriate formative assessment methods for the student's specific project. This would provide students with a lot more agency in deciding how they would assess themselves and how their teacher would assess them, but other logistical constraints such as time and classroom management would emerge. As it stands, my dissertation has found some common ground between student-driven and teacher-driven formative assessment, but I think it would be interesting to study an implementation that skews towards student-driven assessment.

How might elementary school students think about driving formative assessment and documentation for themselves? What additional tools or structures might elementary school students need, in order to be productive pondering about assessment of their own learning?

Epilogue: Documentation as "Thinking Outside of the Box"

In this concluding section, I reflect on a statement Kian Tat made during my interview with him, after Phase 3's implementation. Midway during the interview, he mentioned that taking photographs during his Scratch coding activity helped him "think outside the box," and more broadly on potential applications of coding. Our conversation continued as he tried to piece together how taking photographs in the middle of coding led him to be more perceptive about the wider notion of coding:

> Kian Tat: If we face any problems, we'll go to the code stuff (Scratch platform) and then the coding chart (Scratch toolbar) where you choose what (codes) you want to put in. And then after that, you design your own codes. [Scratch has features to design your own functions.] And it could be useful in future. … It gives you the basics to make games, so that in future you can be a game maker!

Kian Tat ended with an idea that learning to code on Scratch could lead him to an occupation (game maker). Although Kian Tat did not explicitly show how taking photographs of his codes led him to better understand a certain coding concept or skill required in his project, this spurt of intrinsic motivation that he experienced and phrased as "thinking out of the box" is the ultimate goal that I am trying to reach - student-driven, productive, meaningful documentation. For young students to be driven to document, it needs to hold meaning to them. This meaning could emerge to students in the form of a sudden epiphany moment, or a newfound interest in an unexplored pathway, and documentation will be the vehicle that propels them towards this personal intrinsic goal.

References

Ackermann, E. (2001). Piaget's constructivism, Papert's constructionism: What's the difference. *Future of learning group publication, 5*(3), 438.

Ackermann, E. (2004). Constructing knowledge and transforming the world. In (Tokoro, M.; Steels, L. Eds.). *A learning zone of one's own: Sharing representations and flow in collaborative learning environments* (pp. 15-37). IOS Press, Amsterdam, Berlin. Oxford, Tokyo, Washington, DC.

Anastopoulou, S., Sharples, M., & Baber, C. (2003). Multimodality and Learning: linking science to everyday activities. *HCII 2003*.

Andrade, H. G. (2000). Using rubrics to promote thinking and learning. *Educational leadership, 57*(5), 13-19.

Andrade, H., & Brookhart, S. M. (2016). The role of classroom assessment in supporting self-regulated learning. In *Assessment for learning: Meeting the challenge of implementation* (pp. 293-309). Springer, Cham.

Bandura, A. (2001). Social cognitive theory: An agentic perspective. *Annual review of psychology, 52*(1), 1-26.

Bednar, A.K., Cunningham, D., Duffy, T.M., & Perry, J.D. (1991). Theory into practice: How do we link? In G.J. Anglin (Ed.), *Instructional technology: Past, present, and future*. Englewood, CO: Libraries Unlimited.

Bergner, Y., Abramovich, S., Worsley, M., & Chen, O. (2019). What are the learning and assessment objectives in educational Fab Labs and Makerspaces?. In Proceedings of FabLearn 2019 (pp. 42-49).

Bevan, B., Petrich, M., & Wilkinson, K. (2014). Tinkering is serious play. *Educational Leadership, 72*(4), 28-33.

Black, P., & Wiliam, D. (1998). Assessment and classroom learning. *Assessment in Education: Principles, Policy & Practice, 5*(1), 7-74.

Blau, I., & Shamir-Inbal, T. (2017). Re-designed flipped learning model in an academic course: The role of co-creation and co-regulation. *Computers & Education, 115*, 69-81.

Blikstein, P. (2018). Maker movement in education: History and prospects. *Handbook of Technology Education*, 419-437.

Blikstein, P. (2015). Computationally Enhanced Toolkits for Children: Historical Review and a Framework for Future Design. *Foundations and Trends Human–Computer Interaction 9(1)*, 1-68.

Blikstein, P., & Krannich, D. (2013, June). The makers' movement and FabLabs in education: experiences, technologies, and research. In *Proceedings of the 12th international conference on interaction design and children* (pp. 613-616).

Bloomberg, L. D., & Volpe, M. (2018). Completing your qualitative dissertation: *A Road Map from Beginning to End.* Sage Publications.

Bower, G.H., & Hilgard, E.R. (1981). *Theories of learning* (5th ed.). Englewood Cliffs, NJ: Prentice-Hall.

Brennan, K., Haduong, P., & Veno, E. (2020). *Assessing creativity in computing classrooms*. Cambridge, MA: Creative Computing Lab.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative research in psychology, 3*(2), 77-101.

Buechley, L., Eisenberg, M., Catchen, J., & Crockett, A. (2008, April). The LilyPad Arduino: using computational textiles to investigate engagement, aesthetics, and diversity in computer science education. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 423-432).

Carter, T. M. (2013). Use what you have: authentic assessment of in-class activities. *Reference Services Review, 41*(1), 49-61.

Cavalcanti, G. (2013). Is it a Hackerspace, Makerspace, TechShop, or FabLab. *Make, May,* 22. Retrieved from https://makezine.com/2013/05/22/the-difference-between-hackerspaces-makerspaces-techshops-and-fablabs/.

Chan, M. M., & Holbert, N. (2019). Exploring modalities of reflection using social online portfolios for maker-oriented project-based learning. In *Proceedings of FabLearn 2019* (pp. 172-175). ACM.

Chan, M. M. & Holbert, N. (2020, May). Insights on Online Mobile Maker Portfolios for Process Documentation in K-5 Constructionist Learning Environments. In *Proceedings of Constructionism 2020*. Dublin, Ireland.

Chan, M. M., & Holbert, N. (2020). Towards Student-Driven Formative Assessment Practices across School and Afterschool Makerspaces. In *Proceedings of FabLearn 2020*. ACM.

Chang, S., Keune, A., Peppler, K., Maltese, A., McKay, C., & Regalla, L. (2015). Open portfolios: Maker education initiative full research brief series.

Chick, N. (2013). Metacognition. Vanderbilt University Center for Teaching. Retrieved [April

2nd, 2022] from https://cft.vanderbilt.edu/guides-sub-pages/metacognition/.

Clapp, E. P., Ross, J., Ryan, J. O., & Tishman, S. (2016). *Maker-centered learning: Empowering young people to shape their worlds.* John Wiley & Sons.

Collins, A. (1991). Portfolios for Biology Teacher Assessment. *Journal of Personnel Evaluation in Education, 5*(2), 147-68.

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS quarterly*, 319-340.

Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User acceptance of computer technology: a comparison of two theoretical models. *Management science, 35*(8), 982-1003.

DeBarger, A. H., Penuel, W. R., & Harris, C. J. (2013, September). Designing NGSS assessments to evaluate the efficacy of curriculum interventions. In *Invitational Research Symposium on Science Assessment, Washington, DC. Retrieved from http://www.k12center.org/rsc/pdf/debarger-penuel-harris.pdf Gobert, J., & Buckley, B.(2000). Introduction to model-based teaching and learning. International Journal of Science Education* (Vol. 22, No. 9, pp. 891-894).

D'Mello, S. (2013). A selective meta-analysis on the relative incidence of discrete affective states during learning with technology. *Journal of Educational Psychology, 105*(4), 1082.

Doppelt, Y. (2009). Assessing creative thinking in design-based learning. *International Journal of Technology and Design Education, 19*(1), 55-65.

Dorn, C. M., Sabol, R., Madeja, S. S., & Sabol, F. R. (2014). *Assessing expressive learning: A practical guide for teacher-directed authentic assessment in K-12 visual arts education.* Routledge.

Dougherty, D. (2013). The maker mindset. In M. Honey & D. E. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators* (pp. 7–11). New York: Routledge.

Duckworth, A. L., & Yeager, D. S. (2015). Measurement matters: Assessing personal qualities other than cognitive ability for educational purposes. *Educational Researcher, 44*(4), 237-251.

Duffalo, A. (2010, February 5). Play: What's to be learned from kids? Retrieved August 4, 2019, from https://walkerart.org/magazine/play-whats-to-be-learned-from-kids-part-1 Interview with Edith Ackermann.

Engeström, Y. (2001). Expansive learning at work: Toward an activity theoretical reconceptualization. *Journal of education and work, 14*(1), 133-156.

Engeström, Y., & Sannino, A. (2010). Studies of expansive learning: Foundations, findings and future challenges. *Educational Research Review, 5*(1), 1-24.

Ertmer, P. A., & Newby, T. J. (2013). Behaviorism, cognitivism, constructivism: Comparing critical features from an instructional design perspective. *Performance improvement quarterly, 26*(2), 43-71.

Fereday, J., & Muir-Cochrane, E. (2006). Demonstrating rigor using thematic analysis: A hybrid approach of inductive and deductive coding and theme development. *International journal of qualitative methods, 5*(1), 80-92.

Flavell, J. (1976). Metacognitive aspects of problem-solving. In L. Resnick (Ed.), *The Nature of Intelligence*. Hillsdale, NJ: Erlbaum Assoc.

Flavell, J. H., Miller, P. H., & Miller, S. A. (1985). *Cognitive development* (Vol. 338). Englewood Cliffs, NJ: Prentice-Hall.

Fraile, J., Panadero, E., & Pardo, R. (2017). Co-creating rubrics: The effects on self-regulated learning, self-efficacy and performance of establishing assessment criteria with students. *Studies in Educational Evaluation, 53*, 69-76.

Freire, P. (1972). *Pedagogy of the oppressed.* New York: Herder and Herder.

Frey, B. (2018). Authentic Assessment. In *The SAGE encyclopedia of educational research, measurement, and evaluation* (Vols. 1-4). Thousand Oaks, CA: SAGE Publications, Inc. doi: 10.4135/9781506326139

Frey, B. B., Schmitt, V. L., & Allen, J. P. (2012). Defining authentic classroom assessment. *Practical Assessment, Research, and Evaluation, 17*(1), 2.

Gardner, H. (1989). Zero-based art education. *Studies in Art Education: A Journal of Issues and Research, 30*(2).

Granott, N. (1993). *Microdevelopment of co-construction of knowledge during problem solving: puzzled minds, weird creatures, and wuggles* (Doctoral dissertation, Massachusetts Institute of Technology).

Greene, J. A., Hutchison, L. A., Costa, L. J., & Crompton, H. (2012). Investigating how college students' task definitions and plans relate to self-regulated learning processing and understanding of a complex science topic. *Contemporary Educational Psychology, 37*(4), 307-320.

Hadad, R., Thomas, K., Kachovska, M., & Yin, Y. (2020). Practicing formative assessment for computational thinking in making environments. *Journal of Science Education and Technology, 29*(1), 162-173.

Harel, I. E., & Papert, S. E. (1991). *Constructionism.* Ablex Publishing.

Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of educational research, 77*(1), 81-112.

Havnes, A., Smith, K., Dysthe, O., & Ludvigsen, K. (2012). Formative assessment and feedback: Making learning visible. *Studies in Educational Evaluation, 38*(1), 21-27.

Holbert, N., Berland, M., & Kafai, Y. B. (Eds.). (2020). *Designing constructionist futures: The art, theory, and practice of learning designs.* MIT Press.

Honey, M., & Kanter, D. E. (Eds.). (2013). *Design, make, play: Growing the next generation of STEM innovators.* Routledge.

Hung, H. T., Chiu, Y. C. J., & Yeh, H. C. (2013). Multimodal assessment of and for learning: A theory‐driven design rubric. *British Journal of Educational Technology, 44*(3), 400-409.

Jacobs, J. E., & Paris, S. G. (1987). Children's metacognition about reading: Issues in definition, measurement, and instruction. *Educational psychologist, 22*(3-4), 255-278.

Jewitt, C. (2003). Re-thinking assessment: Multimodality, literacy and computer-mediated learning. *Assessment in education: Principles, policy & practice, 10*(1), 83-102.

Jonassen, D. H. (1997). Instructional design models for well-structured and ill-structured problem-solving learning outcomes. *Educational technology research and development, 45*(1), 65-94.

Jonassen, D. H. (1991b). Objectivism vs constructivism: Do we need a new philosophical paradigm. *Educational technology research and development, 39*(3), 5–14.

Kafai, Y. B. (2006). Constructionism. In K. R. Sawyer (Ed.). *The Cambridge handbook of the learning sciences*. Cambridge University Press.

Kafai, Y., Fields, D., & Searle, K. (2014). Electronic textiles as disruptive designs: Supporting and challenging maker activities in schools. *Harvard Educational Review, 84*(4), 532-556.

Katz, I., & Assor, A. (2007). When choice motivates and when it does not. *Educational Psychology Review, 19*(4), 429-442.

Keune, A. & Peppler, K. (2017). Maker Portfolios as Learning and Community-Building Tools Inside and Outside Makerspaces In *Smith, B. K., Borge, M., Mercier, E., and Lim, K. Y. (Eds.). (2017). Making a Difference: Prioritizing Equity and Access in CSCL, 12th International Conference on Computer Supported Collaborative Learning (CSCL) 2017*, Volume 2. Philadelphia, PA: International Society of the Learning Sciences.

Kim, Y. J., Murai, Y., & Chang, S. (2020). Embedded Assessment Tools for Maker Classrooms: A Design-Based Research Approach. Retrieved from https://edarxiv.org/4h3n7/

Kuznetsov, S., & Paulos, E. (2010, October). Rise of the expert amateur: DIY projects, communities, and cultures. In *Proceedings of the 6th Nordic conference on human-computer interaction: extending boundaries* (pp. 295-304).

Lan, W. Y. (1998). Teaching self-monitoring skills in statistics. *Self-regulated learning: From teaching to self-reflective practice*, 86-105.

Martin, L. (2015). The promise of the maker movement for education. *Journal of Pre-College Engineering Education Research (J-PEER), 5*(1), 4.

Maxwell, J. A. (2008). Designing a qualitative study. *The SAGE handbook of applied social research methods, 2*, 214-253.

Meer, N., & Chapman, A. (2015). Co-creation of Marking Criteria: Students as Partners in the

Assessment Process. Business and Management Education in HE, 0(0), 1–15. https://doi.org/10.11120/bmhe.2014.00008

Meyer, E., Abrami, P. C., Wade, C. A., Aslan, O., & Deault, L. (2010). Improving literacy and metacognition with electronic portfolios: Teaching and learning with ePEARL. *Computers & Education, 55*(1), 84-91.

Moskal, B. M. (2003). Recommendations for developing classroom performance assessments and scoring rubrics. *Practical Assessment, Research & Evaluation, 8*(14), Retrieved from https://scholarworks.umass.edu/pare/vol8/iss1/14/.

Muis, K. R., & Duffy, M. C. (2013). Epistemic climate and epistemic change: Instruction designed to change students' beliefs and learning strategies and improve achievement. *Journal of Educational Psychology, 105*(1), 213.

Murai, Y., Kim, Y. J., Chang, S., & Reich, J. (2020). Principles of Embedded Assessment in School-Based Making. Retrieved from https://edarxiv.org/amvs2/

National Research Council. (2009). *Learning Science in Informal Environments: People, Places, and Pursuits.* Washington, D.C.: The National Academies Press. Retrieved from www.nap.edu/catalog.php?record_id=12190.

National Research Council. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research.* National Academies Press.

Panadero, E., & Alonso-Tapia, J. (2013). Self-assessment: Theoretical and practical connotations. When it happens, how is it acquired and what to do to develop it in our students. *Electronic Journal of Research in Educational Psychology, 11*(2), 551–576. https://doi.org/10.14204/ejrep.30.12200

Panadero, E., & Jonsson, A. (2013). The use of scoring rubrics for formative assessment purposes revisited: A review. *Educational Research Review, 9*, 129-144.

Papert, S. (1980). *Mindstorms: Computers, children, and powerful ideas.* NY: Basic Books.

Papert, S. (1993). *The children's machine: Rethinking school in the age of the computer.* New York: BasicBooks.

Pea, R. D. (1987). *Logo programming and problem solving.* Technical Report.

Pellegrino, J. W. (2018). Assessment of and for learning. In *International Handbook of the Learning Sciences* (pp. 410-421). Routledge.

Resnick, M., & Rusk, N. (1996). The computer clubhouse: Preparing for life in a digital world. *IBM Systems Journal, 35*(3.4), 431-439.

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.

Shroff, R. H., Deneen, C. C., & Ng, E. M. (2011). Analysis of the technology acceptance model in examining students' behavioural intention to use an e-portfolio system. *Australasian Journal of Educational Technology, 27*(4).

Shute, V. J. (2008). Focus on formative feedback. *Review of educational research, 78*(1), 153-189.

Singapore Ministry of Education. (2015, October). *Contact: The Teacher's Digest.* Preparing students to be future ready.

https://www.moe.gov.sg/-/media/files/publications/contact_oct15.pdf.

Sipitakiat, A., Blikstein, P., & Cavallo, D. (2002). The GoGo Board: Moving towards highly available computational tools in learning environments. In *Proceedings of Interactive Computer Aided Learning International Workshop.*

Sipitakiat, A., Blikstein, P., & Cavallo, D. P. (2004). GoGo board: augmenting programmable bricks for economically challenged audiences. s. In *Proceedings of ICLS 2004*. USA, 2004.

Solomon, C., Harvey, B., Kahn, K., Lieberman, H., Miller, M. L., Minsky, M., ... & Silverman, B. (2020). History of logo. *Proceedings of the ACM on Programming Languages, 4*(HOPL), 1-66.

Soster, T., Fuhrmann, T. & Campos, F. (2020, January). Mapping Assessment Practices in School Makerspaces. In *Proceedings of FabLearn Asia 2020*. ACM.

Stepich, D. A., & Newby, T. J. (1988). Analogical instruction within the information processing paradigm: effective means to facilitate learning. *Instructional Science, 17*, 129–144.

Swain, J. (2018). *A hybrid approach to thematic analysis in qualitative research: Using a practical example.* SAGE Publications Ltd.

Tseng, T. (2016). *Making make-throughs: documentation as stories of design process* (Doctoral dissertation, Massachusetts Institute of Technology).

Van Boekel, M., Weisen, S., & Hufnagle, A. (2021). Feedback in the Wild: Discrepancies Between Academics' and Students' Views on the Intended Purpose and Desired Type of Feedback. In *Proceedings of the 15th International Conference of the Learning Sciences - ICLS 2021*. International Society of the Learning Sciences.

Van Leeuwen, T. (2015). Chapter 21: Multimodality. In D. Tannen, H. E. Hamilton, & D.

Schiffrin (Eds.), *The Handbook of Discourse Analysis* (pp. 447–465). essay, John Wiley & Sons, Inc.

Van Leeuwen, T., & Kress, G. (2001). Multimodal discourse: the modes and media of contemporary communication. *London: Arnold.*

Wiliam, D. (2007). Keeping learning on track: Formative assessment and the regulation of learning. In F. K. Lester, Jr. (Ed.), *Second handbook of mathematics teaching and learning* (pp. 1053–1098). Greenwich, CT: Information Age Publishing.

Winne, P., & Azevedo, R. (2014). Metacognition. In R. Sawyer (Ed.), *The Cambridge Handbook of the Learning Sciences* (Cambridge Handbooks in Psychology, pp. 63-87). Cambridge: Cambridge University Press. doi:10.1017/CBO9781139519526.006.

Wolf, D. (1989). Portfolio assessment: Sampling student's work. *Educational Leadership, 45*(4), 35–39.

Xerou, E., Papadima-Sophocleous, S., & Parmaxi, A. (2016). A social constructionist approach to teaching and learning vocabulary for Italian for academic purposes.

Appendix A

Observation Guide for Phases 1, 2 and 3

For Phase 1:

- What kinds of prompts do students need, regarding documentation methods and their choice(s) of documentation?
- How do students decide on the documentation method(s) they want to use?
- How often do students need to be reminded about their choice of documentation method once they start prototyping / building?

For Phase 2:

- How do students decide on the documentation method(s) they want to use?
- (for students working in groups) Do students talk about documentation with their groupmates? How do they discuss about it?
- What kinds of prompts do teachers provide to students in class?
- What feedback do teachers provide to students in class?
- What features of the CoCreator App do students actively use?
- How do students respond to their teachers' / mentors' feedback?

For Phase 3:

- (for students working in groups) Do students talk about documentation with their groupmates? How do they discuss about it?
- How do students divide roles in their groups?

    - Does this affect documentation? If yes, how so?
- What are students' documentation steps when they select an artifact to document?
- What kinds of prompts do teachers provide to students in class?
- What feedback do teachers provide to students in class?
- How do students respond to their teachers’ feedback?

Appendix B

Interview Protocol (Student) for Phase 1

30 mins

This interview occurs after the observation sessions are complete, and is conducted online via a Zoom video call too. This 1:1 interview with the researcher will be conducted preferably 0-5 days after the observation sessions are complete.

Hi (student's name), my name is Monica. Could you tell me more about yourself, eg. which grade you're in, how often you're involved in making? What sorts of projects do you like to make?

Could you please give me a quick recap on what your maker project was?

Could you walk me through how you identified specific skills or concepts (use a skill or concept that the student had written on his/her concept map) you need to learn more about in order to make your project?

During the maker activity, I noticed you (referred to / hardly referred to) the concept map you created. Could you show me the knowledge or skill that you had planned to demonstrate when you were completing the concept map?

To what degree do you think the concept map was helpful?

How do you think the solar system visuals worked?

Would you change the planets or moons to something else?

Would you rather have empty boxes to fill out, rather than a sun / planet / moon?

Do you think it was helpful to show your teacher how you'd like to learn a concept or skill?

Do you think it's helpful to eventually show your learning in a way that might be different from your friends in class?

How did you feel when you decided on a particular assessment strategy, and your friend in class had a different assessment strategy?

Did you discuss with other peers about how your project assessments are similar or different?

How do you think this concept mapping experience could be improved?

Talk me through your design and how you made your project.

I noticed that your project is _____ here - how did you come to this decision to make it this way?

(Could pose contradictory statements or play devil's advocate)

Appendix C

Interview Protocol (Student) for Phase 2

30 mins

This 1-1 interview is conducted online via a Zoom video call, after the observation sessions are complete, and towards the end of the students' maker program.

Hi (student's name), my name is Monica. Could you tell me more about yourself, eg. which grade you're in, how often you're involved in making? What sorts of projects do you like to make?

- Could you please give me a quick recap on what your maker project was during the program?
- Could you walk me through how you identified specific skills or concepts (use a skill or concept that the student had written on his/her concept map) you need to learn more about in order to make your project?
- During the maker activity, I noticed you (referred to / hardly referred to) the CoCreator App. Could you show me the knowledge or skill that you had planned to demonstrate when you were documenting on the CoCreator App?
- To what degree do you think the CoCreator App was helpful?
- How do you think the framework visuals worked?
- Say I was your teacher/mentor during the maker activity. Do you think it's helpful to show your teacher how you'd like to learn a concept or skill?

- Do you think it’s helpful to eventually show your learning in a way that might be different from your friends in class?
- How do you think this experience of using the CoCreator App could be improved?
- Talk me through your design and how you went about building your maker project.
- I noticed that your project is _____ here - how did you come to this decision to make it this way?

Appendix D

Interview Protocol (Maker Educator) for Phase 2

45 mins

This interview occurs after the observation sessions are complete, and is conducted online via a Zoom video call. This 1:1 interview with the researcher will be conducted preferably 0-5 days after the observation session is complete.

Hi (teacher's name), my name is Monica. Could you tell me more about yourself, eg. which grade you teach, how long you've been teaching STEAM / maker education?

- What sorts of projects do you usually have students make?
- Previously, what forms of formal and informal assessment methods have you used for your maker programs / classes?
- How was your experience using this assessment co-creation process?
- Were there any particular instances of interactions with your students that stood out? What are some examples?
- Could you walk me through how you would facilitate goal-setting and topic-brainstorming with your students using this process?
- What was challenging about assessment co-creation?
- This could be personal challenges, and challenges with student interaction etc.

- How do you think students progressed throughout the weeks? Did you notice students referring to their concept maps, or did you have to keep reminding them to refer and modify their concept maps?
- How successful do you think the individualized assessment strategies that you co-created with students are for their projects?
- To what degree do you think the concept map was helpful?
- From your perspective, is it helpful that your student shows you how they'd like to learn a concept or skill?
- How do you think this concept mapping and assessment co-creation experience could be improved?
- How might we leverage technologies to facilitate the formative assessment process?

Appendix E

Interview Protocol (Student) for Phase 3

Opening question

Firstly, just want to let you know that there are no right or wrong answers to the questions I'm about to ask you - this is not a test! I will also not share your answers with your friends / teammates or teachers, so I'd like you to tell me your honest thoughts.

- How do you think your design thinking / MakeyMakey project went over the past term?
- What was 1 success you had?
- What was 1 thing you could've done better?
- In your group, were you the documentation leader?
    - If no, who was it?

Diving into Documentation

- [For the documentation leaders] Could you tell me more about how you chose what photos to take of your group?
    - If you think back to when you were doing (insert activity: interviewing / making clay sculptures / brainstorming ideas verbally or through sketching on notebook), what made you decide that this was a photo to take of your team?
        - (Could show them more than 1 photo)
    - "Idk I haven't take picture in a while"
        - Hypothesis / Assumption: haphazard / unstructured

        - Your teacher reminded you to take photos as you were doing the project. Did you need that reminder? Or had you already taken the photos before the reminders?
        - What are the things you know? Did you take photos during the same time in class? [Is it regular]
        - What was happening when you took this photo?
- How did you choose which hashtags to use for an image?
    - What do you notice when you click on a single hashtag to view your past work?
    - [give the students an activity - to probe their reflection process] Using this hashtag, can you tell me the story of building this musical instrument?
        - You mentioned [music / art / coding idea]. Did you know about this before? Can you tell me how that works? [identification of knowledge; connect it to the tool or not]
    - Do you remember how you and your teacher came up with these hashtags? Mr Tang told me it was done on Seesaw. Tell me more about what you thought about when you saw those hashtags?
- What does this slider mean to you? (the motivation level tracker)
    - How about this graph? Did what you marked on Week 2 matter for what you'd mark on Week 3? Why / Why not?
    - I noticed that you listed (these motivation levels) (share screen) about your group. Could you tell me more about how you assigned these numbers? What did

- How did you organize your projects in this CoCreator App? (some students made 1 project; some made multiple; some made 1 new project each week)
    - Did you feel that making a new project each week was more useful than making 1 project with multiple weeks? Was it easier to track?

What they learnt - weave it in the questions above:

- What did you learn about coding music on Scratch?
- What did you learn about connecting the wires on MakeyMakey?
- What did you find out about what clay to use?

On Feedback

- Did you notice your teacher's comments on the app?
    - When did you see those? Were the comments useful?
- I noticed that you didn't write a lot of text in the reflection box, but how might you respond to some of Mr Tang's feedback on the app?
- Usually when Mrs Khoo or Mr Tang gives you feedback in-person, how do you respond?
    - Was this useful to you? [what kind of conversation did you have with your teacher]
    - Do you ask them clarifying questions? Or you just follow their instructions?
- If Mr Tang gives you feedback in-person that sounds different from what he wrote in the CoCreator App, how do you think you'd respond?

Improvement Suggestions

- What else might you like to show (someone who is not in our class) about your maker project?
- So this CoCreator App was designed to help you record your making / design thinking processes more in class. Apart from the app sometimes shutting down or that you had to click multiple times to take a photo, what else do you think could be better about this app? [frame it as "you're the expert using the app and making the instrument"]

Appendix F

Interview Protocol (Maker Educator) for Phase 3

Open the interview with a more general question: How do you feel so far about the past 3 weeks?

Lesson goals

- What were the main learning objectives you prepared for the past 3 classes, and to what extent do you think students achieved / completed the goals you'd set?
    - (If Art or Music was not specifically mentioned) What were your learning objectives for the core subject you teach?
- What was a particularly challenging area / lesson / concept for you to get across to your students? Why?
    - How did you gauge students' understanding during that lesson?
- What are your learning objectives for the next 4 classes? (this question will be asked again at the end of the term to compare teachers' responses)
    - (If Art or Music was not specifically mentioned) What would your learning objectives be for the core subject you teach?
- Which part / which learning objective do you think students would find most challenging?
    - How do you plan to track students' progress for this learning objective?

Collaboration with students

- [For Mr Tan] How did you collaborate with students to figure out the hashtag dictionary to come up with hashtags / keywords for photos they'd take of their project? I recall that you did this on MOE's Student Learning Space. Could you show me how you sourced for students' ideas, what they came up with, what they voted on etc.? (screenshare if possible)
    - What challenge(s) did you face when collaborating with students to come up with hashtag ideas?
    - Were these hashtags updated weekly? What was the cadence / frequency?
    - Do you think students are using these hashtags in the way you thought they would?
        - What could improve in how they use these hashtags?
        - What could improve in terms of forming these hashtags? (this could be on hindsight, or could be next steps to take for subsequent weeks)
- When you're collaborating with students on _____, what do you have in mind to achieve?
    - Could you describe how you collaborate with students when they are learning about design thinking / about the Makey Makey / about how to interview non-teaching staff?
- How would you describe your style of guiding students when they are working on the group maker project?

Feedback

- What is your preferred mode when providing feedback?
    - Verbal / text / in-person (live) / writing / via SLS?
- I'd like to understand how you provide feedback to students, and what modes / technologies you use. Would you please walk me through a couple of examples?
    - [For Mr Tan] I recall that you mentioned you prefer providing verbal feedback. Could you please explain more? How do you provide verbal feedback?
    - Are there any instances where you provide asynchronous or textual feedback in maker ed classes?
    - How is the CoCreator App supporting how you provide feedback? Where is it falling short?
- [For Mrs Lee] I noticed that you asked students specifically to upload videos or photos of them interviewing the non-teaching staff members during Lesson 3 onto Seesaw (and onto the CoCreator App), the LMS that the school uses to communicate with parents regarding student work.
    - What is your main goal when you ask students to upload to Seesaw? Would it be for visibility to parents or the principal?
    - How do you decide what students should upload onto Seesaw?
    - How is the CoCreator App supporting how you provide feedback? Where is it falling short?

Using the CoCreator App

- Could you describe how frequently you use the CoCreator App in a week? (It's okay if the answer is hardly)
- What have you noticed from students' posts?
- How about the student reflections?
- To you, how helpful is the students' self-reported motivation level for a progress update?
    - If it's not very helpful, what would make it more effective for you to figure out students' confidence level at a particular concept / skill / topic?

Formative Assessment

- What do you want/need to see to know that your students are achieving your learning objectives?
    - Is the CoCreator App helping you see what you want to see in your students?
- Do you have rubrics or criteria to guide you?

Appendix G

Coding Scheme

Code Family: Feedback

Code	Sub-Code	Definition	Origin of Code
Task Feedback		The teacher provides students with information about whether their work is correctly executed or not	(Hattie and Timperley, 2007)
Process Feedback		The teacher encourages deeper reflection from students on the extent of success to which a task was done and areas for improvement	(Hattie and Timperley, 2007)
Self-Regulation Feedback		The teacher challenges students to self-assess their work and develop self-directed learning skills	(Hattie and Timperley, 2007)
Praise/Self Feedback		The teacher focuses more on the student rather than the task at-hand, and may not necessarily encourage students to invest more effort in a task	(Hattie and Timperley, 2007)
Style of Feedback	Encouraging	The teacher wrote positive comments meant to motivate the student	Emergent from data
	Checking in	The teacher suggests that the student follows up either on the application or in class	Emergent from data
	Troubleshooting	The teacher points out where a student may be stuck or is doing something wrong, unplanned, or unexpected	Emergent from data
Synchronous feedback		The teacher provides feedback in real time	Emergent from data
Asynchronous feedback		The teacher provides feedback through a platform, and the student views it a while later	Emergent from data
Discourse about feedback		The student or teacher recounts how they receive or provide feedback respectively	Emergent from data
Peer feedback		The student receives feedback from his groupmate / classmate / peer	Emergent from data

Code Family: Documentation Practices

Code	Sub-Code	Definition	Origin of Code

Work-in-progress		The student documents or discusses something unfinished, i.e. a work-in-progress	Emergent from data
Final product		The student documents or discusses his final product	Emergent from data
Presentation		The student documents something for the sake of the (typically final) presentation OR the student intends to document to prepare for a presentation later	Emergent from data
Group dynamics		The student thinks about and/or asks his teammates when he documents, or his action is influenced by his teammate's instruction, or the student discusses how his team works	Emergent from data
	Group dynamics when documenting	The students' interactions with one another when they are documenting their projects	Emergent from data
	Group dynamics when not documenting	The students' interactions with one another when they are not documenting their projects	Emergent from data
Document for self		The student documents items that he deems will be useful for himself now or in the near future	Emergent from data
Document for group		The student documents items that he deems will be useful for his group now or in the near future	Emergent from data
Document for teachers		The student documents items that he deems will be useful for his teacher	Emergent from data
Document unrelated items		The student documents other classmates / other things that are not directly related to their own assignment or their group's project	Emergent from data
Collaboration		includes instances of students sharing ideas and suggestions with teammates, with teachers / mentors, with other classmates etc.	Emergent from data
	Student Roles	The student talks about their roles in the group	Emergent from data
	Exchanging Ideas	The student and their teammates explicitly show that they are discussing ideas about their project	Emergent from data
Lack of agency		The student shies away from a task / responsibility	Emergent from data
Elaboration		The student shows that he explains and elaborates further to another peer or teacher about a topic / skill	Emergent from data
Teacher's learning objectives		The teacher's pedagogical aims for a lesson, curriculum, program etc.	Emergent from data
Resolving conflict		The teacher discusses how he/she intervenes when	Emergent from data

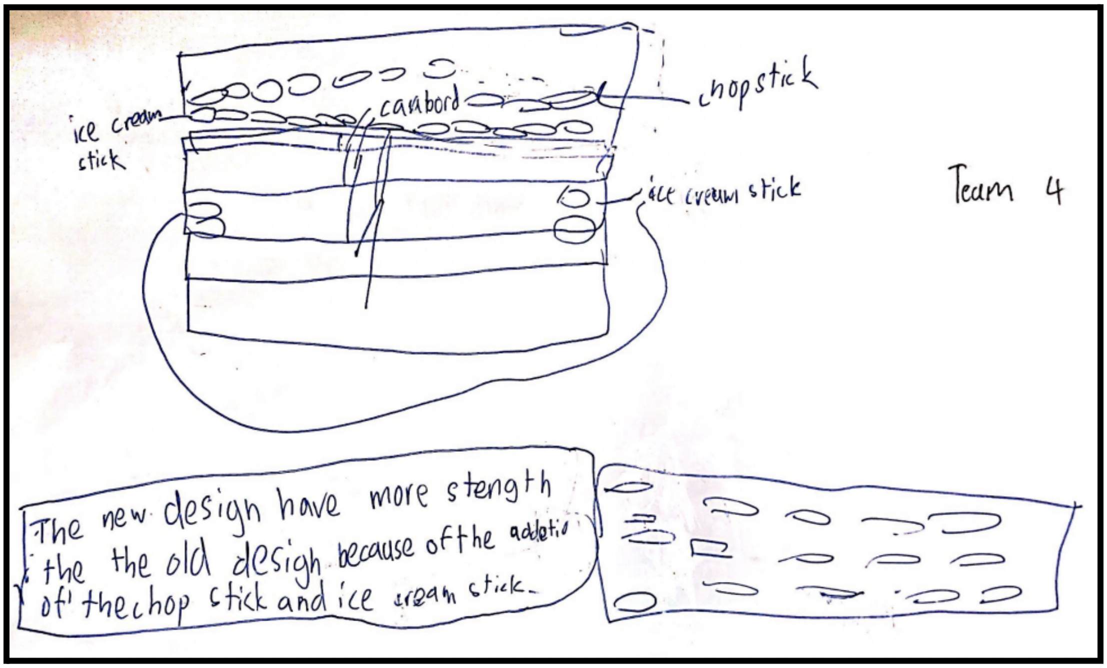
		student conflict arises	
Curriculum development		the teacher observes / intervenes for conflict resolution amongst students, or when students discuss solving arguments within the group	Emergent from data
Teacher’s documentation		The teacher discusses how he/she does lesson-planning, creates lesson content and activities, etc.	Emergent from data
Perspectives on assessment		The teacher documents works-in-progress or class activities	Emergent from data

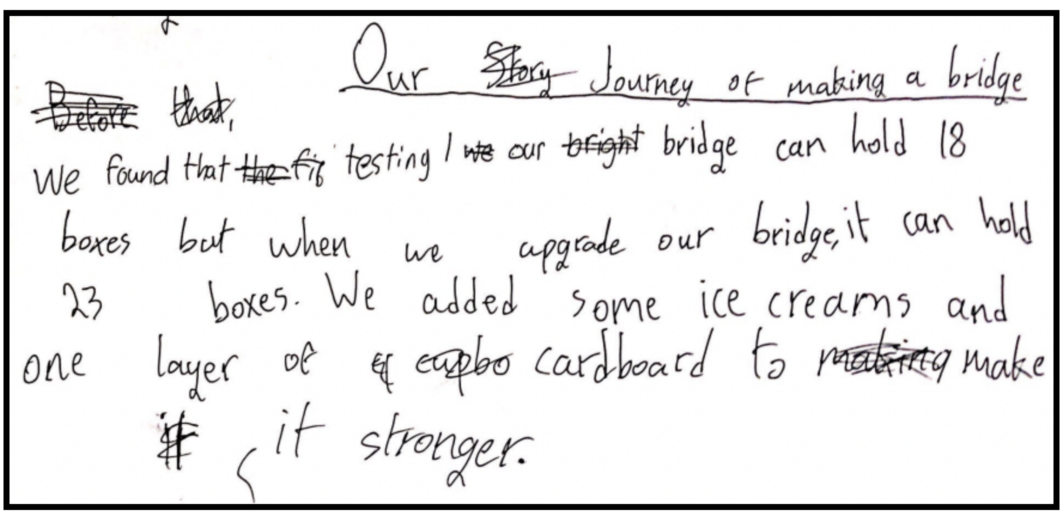
Code Family: CoCreator App Features

Code	**Sub-Code**	**Definition**	**Origin of Code**
Classifying		The student's actions are related to grouping content of photos taken, comments written, type of feedback received. these actions are usually related to how he chooses various hashtags to use	Emergent from data
Taking photos		The student takes photos of his / his group's work, or of activities happening in the makerspace	Emergent from data
Observing other groups		The student looks at what other groups are doing, or discusses how he wants to know about what others are doing	Emergent from data
Confidence level		The student discusses how he uses the confidence level slider OR how confident he was in a certain task during the project	Emergent from data
Organizing		The student's actions related to organizing work / artifacts / photos, actions related to folders. eg. putting all the photos in one folder on the app	Emergent from data
Reflection		The student talks about what they would do or improve on on hindsight	Emergent from data
Feature suggestions		The student's suggestions for features to improve documentation, feedback	Emergent from data
User experience		The student talks about pros and/or cons of his experience using the CoCreator App interface	Emergent from data

Appendix H

Additional artifacts from Brendan & Iman's project




Our ~~Story~~ Journey of making a bridge

~~Before that,~~ We found that ~~the fir~~ testing / ~~we~~ our ~~bright~~ bridge can hold 18 boxes but when we upgrade our bridge, it can hold 23 boxes. We added some ice creams and one layer of ~~cupbo~~ cardboard to ~~making~~ make it stronger.

Appendix I

Dan's Documentation on the CoCreator App and Slack

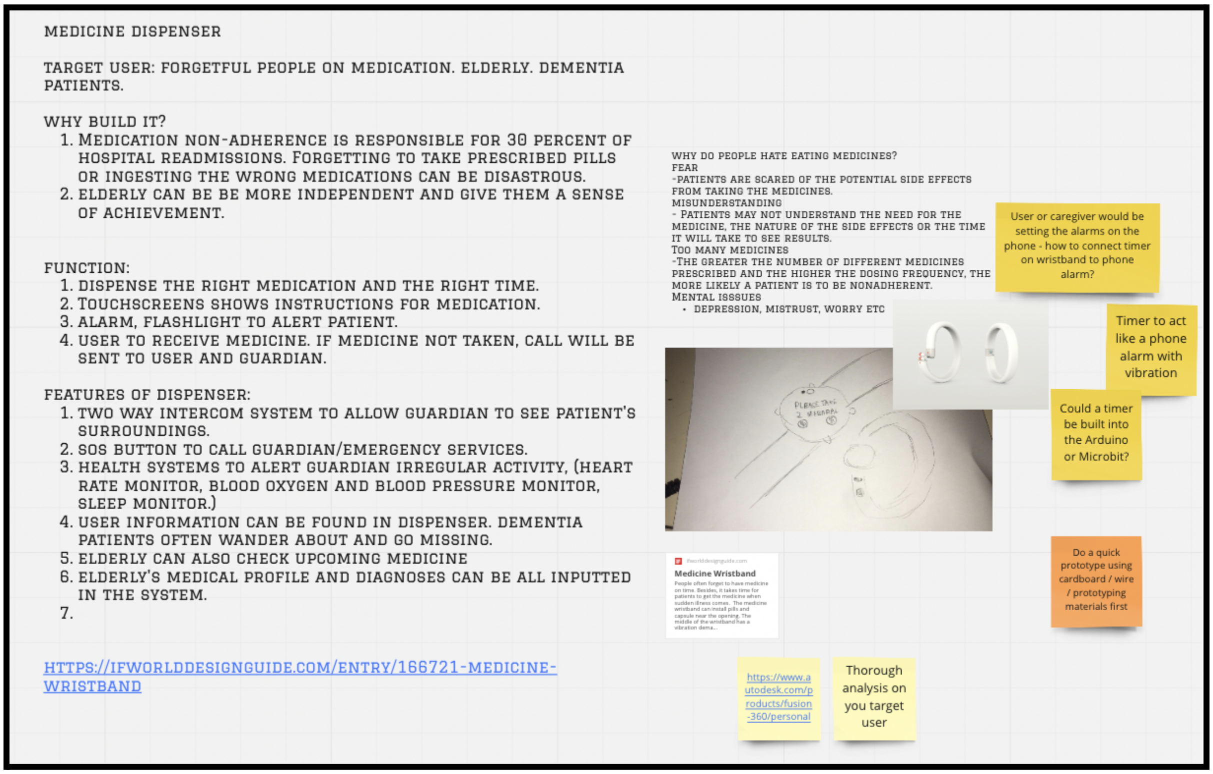
Dan's documentation of coding to himself and his mentor on Slack:

medimind

January 15th, 2021

```
boolean checkTime(int hourAlarm, int minuteAlarm, int secondAlarm) {
  byte second, minute, hour, dayOfWeek, dayOfMonth, month, year;
  readDS3231time(&second, &minute, &hour, &dayOfWeek, &dayOfMonth, &month, &year);
  if (hourAlarm == hour && minuteAlarm == minute && secondAlarm == second) {
    return true;
  } else {
    return false;
  }
}
void shakeUser() {
  printWatchFace("Pls shake watch to allow medicine to enter chamber.");
  tone(A3,196,500);
}
void takeUser1() {
  printWatchFace("Please open watch face to receive MORNING medication.");
  while (checkPill1() == true) {
    tone(A3,247,500);
    millisWait(200);
  }
  tone(A3,196,250);
  printWatchFace("Medicine sucessfully dispensed.");
  millisWait(1000);
}
void takeUser2() {
  printWatchFace("Please open watch face to receive NIGHT medication.");
  while (checkPill2() == true) {
    tone(A3,247,500);
    millisWait(200);
  }
  tone(A3,196,250);
  printWatchFace("Medicine sucessfully dispensed.");
  millisWait(1000);
}
//write servo in the code take user one and two after the millis for the servo to move and open the gate
//  if (digitalRead(PIN_IR) == LOW) {
//       servo1.write(90);
```

Dan’s documentation on the CoCreator App:



Medimind

Point of View Statement

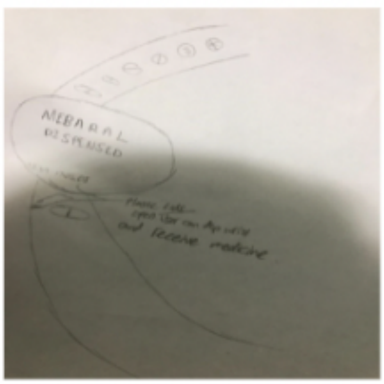
-Elderly's need a way to be prompt and have access to medication wherever and whenever they are at.

Why?

1. According to the WHO, medication adherence has a more direct impact on patient outcomes than the specific treatment itself. Medication adherence affects quality and length of life, health outcomes, and overall healthcare costs. Nonadherence accounts for up to 50% of treatment failures, around 125,000 deaths, and up to 25% of hospitalizations each year.
2. Making elderly more independent. This gives them a sense of purpose and makes them feel more like an individual, giving them a sense of accomplishment.

People like the elderly have trouble with taking the right medication at the right time, which can be resolved by wearing a wearable medicine dispenser. We know we are right when elderly are able to incorporate our product into their life and have their medication related struggles and issue eased, measured by their medication intake and overall well-being.

Proposed Solution



Product description

Medicine to be inputted in the watch itself. When it is time for medicine, light will flicker and alarm will be set off. Vibration will be triggered. When user presses a button at the side, a plastic side will be lifted up and user can flip wrist to receive medicine. Failure to retrieve medicine will increase light flickering intensity and louder alarm. Failure to then receive medicine will notify guardian.

Product will have health features, namely heart rate, blood pressure and blood oxygen monitor. Product will alert guardian if irregular activity is spotted. Product will notify emergency services when there is no movement after a hard fall after a minute.

Two-way intercom system. Guardian can track user location and talk to them via the watch. User can press a button at the side to easily call guardian.

Charging. User can just place watch on a wireless charging platform to charge watch. Watch will light up when fully charged.

Watch to display and tell time like a normal watch when user is not using it to receive medicine.

An app to show watch pill capacity and when to reload medicine for guardian.